Study of Equivalence in Systems Engineering within the Frame of Verification

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Academic Abstract

This dissertation contributes to the theoretical foundations of systems engineering (SE) and exposes an unstudied SE area of definition of verification models. In practice, verification models are largely qualitatively defined based on heuristic assumptions rather than science-based approach. For example, we may state the desire for representativeness of a verification model in qualitative terms of low, medium, or high fidelity in early phases of a system lifecycle when verification requirements are typically defined. Given that fidelity is defined as a measure of approximation from reality and that the (real) final product does (or may) not exist in early phases, we are stating desire for and making assumptions of representative equivalence that may not be true. Therefore, this dissertation contends that verification models can and should be defined on the scientific basis of systems theoretic principles.

Furthermore, the practice of SE is undergoing a digital transformation and corresponding desire to enhance SE educationally and as a discipline, which this research proposes to address through a science-based approach that is grounded in the mathematical formalism of systems theory. The maturity of engineering disciplines is reflected in their science-based approach, such as computational fluid dynamics and finite element analysis. Much of the discipline of SE remains qualitatively descriptive, which may suffer from interpretation discrepancies; rather than being grounded in, inherently analytical, theoretical foundations such as is a stated goal of the SE professional organization the International Council on Systems Engineering (INCOSE). Additionally, along with the increased complexity of modern engineered systems comes the impracticality of verification through traditional means, which has resulted in verification being described as broken and in need of theoretical foundations.

The relationships used to define verification models are explored through building on the systems theoretic lineage of A. Wayne Wymore; such as computational systems theory, theory of system design, and theory of problem formulation. Core systems theoretic concepts used to frame the relationship-based definition of verification models are the notions of system morphisms that characterize *equivalence* between pairs, problem spaces of functions that bound the acceptability of solution systems, and hierarchy of system specification that characterizes stratification. The research *inquisition was in regard to how verification models should be defined* and hypothesized that verification models should be defined through a combination of systems theoretic relationships between verification artifacts; system requirements, system designs, verification requirements, and verification models.

The conclusions of this research provide a science-based metamodel for defining verification models through systems theoretic principles. The verification models were shown to be indirectly defined from system requirements, through system designs and

verification requirements. Verification models are expected to be morphically equivalent to corresponding system designs; however, there may exist infinite equivalence which may be reduced through defining bounding conditions. These bounding conditions were found to be defined through verification requirements that are formed as (1) verification requirement problem spaces that characterize the verification activity on the basis of morphic equivalence to the system requirements and (2) morphic conditions that specify desired equivalence between a system design and verification model. An output of this research is a system theoretic metamodel of verification artifacts, which may be used for a science-based approach to define verification models and advancement of the maturity of the SE discipline.

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General Audience Abstract

We conduct verification to increase our confidence that the system design will do what is desired as defined in the requirements. However, it is not feasible to perform verification on the final product design within the full scope of the requirements; due to cost, schedule, and availability. As a result, we leverage surrogates, such as verification models, to conduct verification and determine our confidence in the system design.

A challenge to our confidence in the system design exists in that we accept the representativeness of the surrogates based on faith alone; rather than scientific proof. This dissertation defines science-based approach to determining the representativeness of substitutes. In the discipline and practice of systems engineering, verification models serve as substitutes for the system design; and verification requirement problem spaces serve as substitutes the requirements.

The research used mathematical principles to determine representative equivalence and to find that a combination of relationship framing is needed for sufficient selection of verification models. The framing includes relationships to the system being engineered and to the substitute conditions under which the verification model is examined relative to the conditions under which the engineered system is expected to operate. A comparison to the state of the discipline and practice to the research findings was conducted and resulted in confirming unique contribution of the dissertation research. In regard to framing the acceptability of verification models, this research established the foundations for a science-based method to advance the field of Systems Engineering.

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To those considering a PhD, ponder this: Often times, you may view your PhD journey and think "There must be a method to the madness." Other times, you may view your PhD journey and think "There IS a madness to the method." And, you come the conclusion that the one item that persists is that "there is always madness." Jovial nature aside, the PhD journey is intended to be an, often maddening, adverse experience; from which overcoming the challenge creates thought leaders and agents of change. Lastly, some words of wisdom from a leader in his field and PhD that graduated under the theoretician from which my research is based: "When you are ready to walk ahead of others, you should not be amazed to notice that nobody is following you immediately; it may take some time for your message to be appreciated!" -Tuncer Ören

Finally, to Wayne A. Wymore (in memory), thank you for providing your theoretical foundations. I hope this dissertation helps to cement your work as core to the discipline and practice of systems engineering. My favorite expression that I learned from you is that we do not understand what we have not modeled.

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1 Introduction and Problem Setting

1.1 Background

The practice of engineering of systems is in the midst of a revolutionary change that includes a transformation to a digital paradigm [1]. Included in this revolution is the transition from *document-based systems engineering* (DBSE) to *model-based systems engineering* (MBSE). The *International Council on Systems Engineering* (INCOSE) defines MBSE as "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" [2]. Within the DBSE approach, *systems engineering* (SE) artifacts are drafted and distributed as a set of textual documents. The current MBSE approach descriptively captures the SE artifacts as data and models.

Descriptive models are used to "specify and/or understand what the system is, what it does, and how it does it" through the use of geometric, spatial, and logical models that capture "requirements, structure, behavior, and parametric constraints associated with a system and its environment, along with the relationships between these elements" [3]. Analytical models are "quantitative or computational in nature and represent the system in terms of a set of mathematical equations" [3]. Although the leading MBSE language, the Systems Modeling Language (SysML), is said to act as a "framework for analysis" [3], SysML does not have a mathematical underpinning. The current MBSE approaches, first, descriptively model SE artifacts and, second, connect to external analytical tools to enable quantitative and computational assessment. Therefore, analysis is reliant on and limited to technical integration of MBSE [4] through parametric and toolchain type capability (e.g., [5]). While MBSE is gaining momentum in both SE research and practice, it lacks formal underlying theoretical foundations that would provide inherent computability [6]. Contrarily, other engineering domains, such as mechanical engineering, have grounded their modeling practices and tools on mathematical foundations (e.g., finite element analysis and computational fluid dynamics). A mathematical underpinning to MBSE would facilitate a transition to integration of descriptive and analytical modeling; and thus, enable leveraging of quantitative and computational methods at the onset of engineering of a system.

The last roughly decade has seen calls for increased mathematical rigor that would enable science-based approaches to engineering of systems [7-15]. This increased emphasis seems to have started with the National Science Foundation (NSF) [8, 16, 17] and calls from INCOSE for SE to be grounded in mathematical rigor [18]. One author has stated that theoretical research is needed in the SE areas of verification and validation, requirements, contracting, risk management, abstraction and elaboration, organization design, and model-based design (with an implication toward MBSE) [9]. Hammami and Edmonson suggest that "mathematical notations could be exploited in order to help disambiguate SE" [14]. Other authors have called for reinvigorated general systems theory (GST) (e.g., [12, 15]). Operationalization of such scientific framework would benefit the practice of SE and strengthen the discipline [15].

There is a rich history of theory for the SE community to draw upon; such as von Bertallanffy's General Systems Theory [19], Mesarovic and Takahara's general [20] and abstract [21] systems theories, and Wymore's theories of SE [22] and system design [23]. However, no other contribution at such scale has been completed since and these works have largely been ignored within the SE community. As an example, although Wymore's research is credited with coining the term MBSE [24, 25], his research is often discussed as being "difficult to translate" [26] and "hard to follow such that only mathematicians are able to read it" [27]. This lack of palatability would likely not come as a surprise to theoreticians such as Wymore. In Wymore's autobiography, he himself suggested that it would take decades or generations for his research to receive recognition, understanding, and implementation within the SE community [28].

However, the call for underpinning the discipline and practice of SE with theoretical foundations is at hand (e.g., [18, 29]), despite the lag in adoption of available theory such as that of Wymore. This dissertation contributes toward the theoretical foundations of SE through building on available mathematical precepts. Specifically, this dissertation focuses on advancing the theory around the unexplored territory of relationship-based definition of verification models.

1.2 Overview of the problem domain

This dissertation will focus mainly on verification, which from the perspective of INCOSE, is used "to provide objective evidence that a system or system element fulfills its specified requirements" [30]. The *National Aeronautics and Space Administration* (NASA) suggests that "verification proves that an end product (whether built, coded, bought, or reused) for any element within the system structure conforms to its requirements or specification" [31] . From the perspective of the *United States Department of Defense* (DOD), verification "provides evidence that the system or system element performs its intended functions and meets all performance requirements listed in the performance specification and functional and allocated baselines" [32]. In summary, verification provides evidence to confirm adherence of the engineered system to system requirements.

Various verification methods are employed to provide confidence [33, 34] of adherence of the engineered system to system requirements. A survey of verification methods defined by INCOSE [30], NASA [31], and DOD [32] suggests that methods include inspection/examination, analysis, demonstration, test, analogy, simulation, and sampling. The term confidence is used here in regard to verification methods because it is rarely feasible to verify adherence to all system requirements with the same verification method or in a purely objective manner; therefore, verification is deemed to be subjective in practice [33, 34]. A large portion of the development cost of engineered systems has been attributed to verification [35, 36]; therefore, the limitation of resources (cost, money, material, etc.) are often considered when selecting the verification method [35-37]. Early verification is used to decrease the possibility of rework or corrective activities, which can incur notable resource consumption [36]. Furthermore, throughout the development of an engineered system, a different verification method may be more relevant or more feasible at a different stage. For example, in the later stages, a verification model in the form of a physical representation of the engineered system may be available, which enables testing, inspection/examination, sampling, and demonstration; whereas in the earlier stages a physical representation may not be feasible and, therefore, a verification model in the form of computational models of the engineered system may be used for simulation and analysis to gain confidence in verification.

Furthermore, there are several technical processes within the discipline of SE that relate to verification and, therefore, to this dissertation. The technical processes that are related to this dissertation include stakeholder needs and system requirements, architecture, design, integration, verification, and validation. The remainder of this section provides a summary overview of each technical processes, relationship to this dissertation, and documentation of inclusion or exclusion from this body of research. The technical processes are discussed in groups as follows: stakeholder needs and requirements are discussed under the term problem formulation; architectural description, design, and integration are grouped together; and verification and validation are grouped together.

The terms stakeholder needs and system requirements are often discussed together as well as with the term problem formulation. Problem formulation is a term used to define the space from which system solutions are defined [38-40], and is commonly associated with the SE technical processes of stakeholder needs definition, system requirements definition, and, in some cases, architectural definition. Stakeholder needs describe the problem space of outcomes desired from the future system and its context [38]. Stakeholder needs are considered out of scope for this dissertation. System requirements are derived from stakeholder needs [38], describe the problem space of functions [38], and define what the system must do [30-32, 38]. SE practice commonly uses natural language, *shall* statements, to define requirements [41]. While stakeholder needs are considered out of scope, system requirements are considered to be in scope for this dissertation.

The terms architectural definition, design, and integration are considered to be interrelated. From the architectural definition, detail is added for the system design definition comprised of components and subsystems which are integrated, verified, and validated. System requirements are decomposed and allocated to components of the engineered system, which is referred to as the architecture definition process [30]. The decomposition and allocation of system requirements to components and to architectural definition is largely considered out of scope for this dissertation. Similar to decomposed and allocated requirements into architecture definition, the design of systems is largely out of scope for this dissertation. This avoids conflict with domain engineering as to designing systems, such as the use of computer aided design (CAD) for mechanical engineering. However, system design in the sense of a structural and behavioral representation of the system being engineered is considered to be in scope for this dissertation. Similarly, integration as in the connection of structural and behavioral representations of the components and subsystems is considered to be in scope for this dissertation. Because the focus of this dissertation is on the system level, minimum attention will be given to detail on integration. Architectural definition, design, and integration are largely considered to be variations, for this dissertation, of the use of the term system design, which is elaborated in detail in later sections.

The terms verification and validation are often grouped together. Verification results in a conclusive statement that the system was "built right" (or not) [30], through understanding the extent to which the engineered system meets the system requirements [30]. Verification is conducted using verification models with varying degree of representativeness of the final product and is conducted in environments with varying degrees of representativeness to the expected operational context. Validation results in a conclusive statement that the "right system was built" (or not) [30], through understanding the extent to which the engineered system fulfils the desired outcomes defined by the stakeholder needs. There may be some implications in this research toward validation in the sense of acceptance testing which is often considered to be part of validation [30]. However, validation is largely considered out of scope for this dissertation; and, verification is considered to be a main focus of this dissertation.

In the context of the INCOSE Handbook [30], Table 1 lists the different technical processes that are related to this dissertation. By direct, I mean that the concepts are core to understanding the dissertation path and will be addressed throughout the dissertation. By indirect, I mean that simple understanding of the concepts is necessary to understand the holistic flow and context. For example, the focus of this dissertation is on verification, which is directly related to system requirements, and as such both verification and system requirements are considered to be directly relevant. Furthermore, an understanding that there are activities in between system requirements and verification (e.g., system modeling) is necessary to understand the overall context. For example, it is crucial to understand that there are varying levels of detail of system models, some which may be used to as a verification model and others which may represent the system design as a decomposition and allocation of system requirements into architectural definition; however, this dissertation will not go into detail on how decomposition and allocation occur and, therefore, architecture is considered indirectly relevant to this dissertation.

Table 1: Subset of SE Technical Processes and their relevance to this dissertation.

SE Technical Process	Description	Relevance
Stakeholder needs	Defines the problem space of outcomes	Indirect
System requirements	Defines the problem space of functions	Direct
Architecture	Results from the decomposition and allocation of system requirements to subsystems and components	Indirect
Design	Contains detail beyond the architecture to specific system solutions	Indirect
Integration	Results from the structural and behavioral composition of components and subsystems to the system level	Indirect
Verification	Provides evidence to confirm adherence of the engineered system to the system requirements	Direct

Validation	Provides evidence to confirm adherence of the engineered system to the stakeholder needs	Indirect

1.3 Problem statement

To understand the challenges with verification, it is crucial to understand that, of the recent calls for increased mathematical rigor in SE, verification was described as being "broken" and in dire need of theoretical foundations [9]. In the referenced article, the author suggests that the complexity of modern engineered systems is increasing to the point that it is impractical to perform verification. Indeed, even if there is a desire to test all possible scenarios, limitations in resources restrict the ability to do so [35, 36]. Rather than test all scenarios, an implication here is that verification must rely on reduced order testing and abstract representations (i.e., verification models) of the final product (system design).

Indeed, in practice, verification often relies on verification models that are abstractions of the final product throughout the system life cycle. For example, a project may use a quarter scale physical model of a rocket for aerodynamic testing in a reduced order wind tunnel in early phases of a project. These abstract representations (of the final product) are often accepted on the basis of subject matter expertise or heuristics rather than being accepted for verification via science-based mechanisms. Given that confidence in the adherence of the final product to system requirements is measured from these, often, abstract verification models, the validity of the adherence should be put into question without science-based understanding.

Furthermore, SE practice suggests that verification models are often expected to be defined in the requirements development phase when the final product does (or may) not exist. Additionally, in the early phases of system development, the actual operational environment may be poorly understood; which necessitates the use of test scenarios (specified as part of verification requirements) that are analogous to the system requirements. For example, NASA may use a surrogate test in a lab on Earth that is analogous to Mars for a verification activity on a surrogate prototype (verification model) rover that is perceived to be analogous to the final product rover. These surrogate analogies used for verification are not quantified within the discipline of SE to the same extent of other disciplines, such as the concept of an equivalent circuit in the more mature discipline of electrical engineering.

Including verification, much of the heuristic-wisdom in SE currently has not been measured. As an example, it is suggested that a verification model only needs to represent the final product as far as the test is concerned [42]; however, the desired representativeness of the verification model to the final product is stated in terms of qualitative, heuristic truth as high-, medium-, low-fidelity. As a result, decisions are made based on truth of which is accepted as conventional SE wisdom, rather than science-based approach. Given that the intent of verification is to gain confidence in adherence of the final product to its system requirements [33], verification requirements in the form of analogous test environments that are analogous to what is specified is the system requirements may be necessary, and verification models may be defined prior to existence of a final product as well as being defined largely on the heuristics of subject matter experts; a concern should be raised as to the lack of scientific-basis for definition of verification models.

1.4 Research question, hypothesis, and objectives

To this point, this dissertation has articulated that there is a transformation of SE in progress, that the SE community is reinvigorating calls for theoretical foundations of the discipline, and that verification relies on abstract representations that are largely accepted based on heuristics rather than science-based approach. Therefore, this dissertation asks the question:

On the basis of what relationships should early-stage verification models be defined?

From the above question, this dissertation ***hypothesizes*** *that early phase verification models should be defined on the basis of a combination of relationships between*:

I. *System Requirements;*
II. *Verification requirements; and*
III. *System Designs*

The implication of the hypothesis is that, rather than on the basis of heuristic and a singular relationship, verification models should be defined on the basis of science-based approach and a combination of relationships to achieve the goal of determining adherence to system requirements.

Objective 1. *Explore the implications of defining a verification model based on system requirements*

Given that verification is conducted to achieve confidence in adherence to system requirements [33], it is clear that there exists a relationship between verification models and system requirements. However, the fact of this relationship being direct or indirect is yet to be determined. If the relationship is direct, then there may exist an assumed orthogonality of system requirements as well as a need to verify the system requirements exactly as stated, which would impact the acceptability of the verification models. If the relationship is indirect, then there is an assumption of equivalence between problem space of functions that underpin the system requirements and its corresponding pair defined as part of a verification requirement, which would also impact the acceptability of verification models.

The consequence of a direct versus indirect relationship between system requirements and verification models was explored as part of this objective. Verification models were defined on the basis of a superset of system requirement and subsets of the system requirements intended to explore the impact of the assumption of orthogonality in system requirements. Furthermore, problem spaces of functions that are proven to be equivalent to the system requirements are defined and the results of defining verification models on the basis of the various problem spaces of functions were compared. These paths enabled exploration of the implications of defining verification models based on system requirements.

Objective 2. *Explore the implications of defining a verification model based on verification requirements*

Given that verification requirements characterize what must be done to confirm adherence to system requirements, it is clear that a relationship between verification models and verification requirements should exist. It is generally accepted that verification requirements are defined on the basis of system requirements. However, if a system requirement may be defined as a mathematical problem space of functions, then perhaps an aspect of a verification requirement is also a problem space of functions. In this sense, verification requirements problem spaces may be formalized and equivalence to the system requirements problem space known. If an aspect of a verification requirement is a problem space of functions, then acceptability of system solution verification models may be bound similar to that between a system design solution and system requirements.

Furthermore, an aspect frequently associated with verification requirements is a documentation of desired fidelity, which is a comparison to reality, of a verification model relative to the final product. The final product does (or may) not exist in early phases and the documentation of desired fidelity remains largely limited to qualitative definition. However, a system design is expected to exist in early phases, from which this dissertation uses the term pedigree in reference to the representativeness of a verification model to a corresponding system design.

Therefore, for this dissertation, a verification requirement is defined as a combination of a problem space of functions that have mathematical characterized equivalence to the system requirements and that bound, in part, the acceptability of verification models; and, verification conditions as to the pedigree of a verification model relative to a system design. From this definition of a verification requirement, the definition of verification models from verification requirements was explored.

Objective 3. *Explore the implications of defining a verification model based on a system design*

A verification model is a representation of a system design that is used to infer adherence of the system design to the system requirements; therefore, representativeness of the verification model to the system design is important to verification. As discussed in previous sections, the representativeness is generally stated on a heuristic-basis and in qualitative terms. This dissertation contends that the representativeness may and should be defined and measured mathematically, which is accomplish through the use of system morphisms. A morphism is a mathematical characterization of equivalence between pairs specified in the same mathematical structure. Verification models and system designs may be defined with the same underlying mathematical structure; and, therefore, morphisms may be used to characterize their representative equivalence.

This dissertation explored the definition of verification models from system designs on the basis of morphic equivalence. Each verification model and system design were defined as a discrete, deterministic, open system in accordance with systems theoretic mathematical structures. Morphisms between the mathematical structures were used to characterize their representative equivalence; thus, exploring the definition of verification models on the basis of system design.

The morphic equivalence established from this objective served as the basis for exploring definition of verification models from verification requirements. Specifically, the verification conditions for pedigree between a verification model and a system design were confirmed on the basis of the morphic equivalence established from this objective. As a result, the verification conditions are referred to as verification requirement morphic conditions throughout the dissertation manuscript.

1.5 Uniqueness of this research

Overall, the research in this dissertation advances the state of the maturity of the discipline of SE through contributing toward scientific foundations.

The literature suggests that (i) increased mathematical rigor is desired for SE (e.g., [18, 29]), (ii) verification is known to be in need of theoretical foundations [9], (iii) verification research in SE literature has been found to be minimal [43], (iv) verification requirements are typically expressed in textual form rather than mathematical or model-based form (e.g., [42]), (v) representativeness of verification models to system design is largely limited to a heuristic-basis and documented in qualitative terms (e.g., [42]), (vi) relationship-based definition of verification models is unexplored research territory, and (vii) limited explicit use of morphisms exists in the SE literature.

Elaboration on the contributions of this dissertation research include:

1) This research contributes to modernizing verification through defining theoretical foundations. In [9], the author expresses a fear that verification has become infeasible, because testing every possible scenario specified in the system requirements in one round and with the same method is impractical. Through leveraging systems theory principles, this dissertation research provides analytical means to characterize equivalence in simplification-based decisions made for verification purposes as compared to the system requirements and system designs.
2) This research uniquely defines verification requirements. In the current education and practice of SE, verification requirements are typically defined textually. No prior research was discovered that defines an aspect of a verification requirement as a problem space of functions. No prior research was discovered that characterizes desired representativeness of a verification model to a system design on the basis of a mathematical expression of equivalence.
3) This research is unique in that representativeness of verification models is largely an unexplored research topic. While in some cases, statistical methods are leveraged; in many cases, representativeness of verification models to corresponding system design

is often left as a heuristic assumption and documented through a qualitative statement. To add to this, the term (high-, medium-, low-) fidelity, a measured comparison to reality, is often used in concert with the verification model as to its representativeness to a final product system design. When considering early phases, in which a final product does (or may) not exist, the use of the term fidelity may not be effective. At minimum, there is no evidence in the literature of SE projects confirming fidelity of early verification models later in the endeavor. Therefore, because system designs do exist in all phases, the term pedigree is expressly used in reference to the representative equivalence between mathematical structures that underpin system designs and verification models.

4) This research is unique in that it is generally heuristically assumed that verification models have relationships to system requirements, verification requirements, and system designs; however, the extent of the truth of these relationships has not been explored. For example, in the leading MBSE language, SysML, a "test case" is the closest entity to the use of the term verification model in this dissertation, has a "verification" relationship directly with system requirements, and no relationship defined in the language of SysML for the relationship to the system design. And, SysML does not have a theoretical underpinning. In addition to exploring these relationships, this dissertation mathematically characterizes these relationships.
5) Finally, this research is unique in that the use of system morphisms is not currently ingrained as a first principal of the discipline and practice of systems engineering. A need for theoretical advancement within SE has been defined as the need to mathematically characterize elaboration and abstraction [9], which is characterized in this dissertation by morphisms. Furthermore, von Bertalanffy's General Systems Theory [19], suggested that there are domain agnostic mathematical structures that underpin the concept of a system. Despite the fact that Wymore's systems engineering focused systems theory [23] leveraged this domain agnostic understanding, his work largely remains shelved by the SE community. This research is founded on Wymorian systems theory (e.g., [44]) and exposes its practical, first principles in the use of system morphisms for the discipline of SE.

1.6 Manuscript organization and structure

The remainder of this dissertation manuscript is structured as follows:

Chapter 2 describes the results of main findings from review of literature.

Chapter 3 defines the research methodology that includes description of tasks and specific methods utilized.

Chapter 4 provides the results.

Chapter 5 provides a discussion, recommendations for future research, and conclusion.

Appendix provides supporting material such as glossary of terms, theoretical background, example validation code, and mathematical structures and proof.

2 Literature Review

2.1 Key findings

Key finding from review of the literature are as follows:

1. The research question has not been addressed; research has not explored the relationships that should be used to define verification models
2. Research on advancements in verification is limited within SE sources.
3. Verification requirements have only been expressed as problem spaces of functions in research that has led to this dissertation
4. Minimal research exists to mathematically define representativeness of verification models to system designs
5. Use of morphisms in SE is largely implicit rather than being explicitly defined between mathematical structures
6. Wymorian systems theory provides the most comprehensive basis for addressing the research question

2.2 Process

This main process of this review was to define scoping questions around which key words and target venues were selected for conduct of the search of the literature. The scoping questions, key words, and target venues were established in the following sections. This literature review will serve the purpose of confirming existence of the research gap and informing the methods of research employed for this dissertation.

Additionally, extensive prior research and review of the literature are leveraged. In particular a systematic literature review on the mathematical foundations of MBSE was previously conducted, which was in comment adjudication at the time of writing this manuscript and was leveraged to capture research that may have been missed by the literature review here. Relevant research from the systematic literature review is considered to be those articles which were categorized as pertaining to verification and articles which contained reference to morphisms. Authors from this relevant research were selected for further exploration of their research that may have provided additional insights.

2.2.1 Scoping questions

Below is a list of framing questions and supporting statements used to scope the literature review are defined in Table 2.

Table 2: Key Questions for Scoping the Literature Review

Key Questions	Supporting statement(s)
To what extent have mathematical relationships been used to define verification models on the basis of: system requirements, verification requirements, system design?	• This question looked to review mathematical relationships used to define verification model. • As part of this question, the current state of practice of SE for relationships was surveyed as a basis for comparison to the mathematical relationships.

To what extent have problem spaces of functions been used to define system requirements and verification requirements?	• An initial assumption here was that aspects of verification requirements have never been treated as a problem space of function • From this initial assumption, it was also assumed that equivalence between system requirements and verification requirements has not been characterized on the basis of both being defined, at least in part, on the basis of problem spaces of functions • This question looked to confirm (or disprove) the above assumptions
To what extent have systems theory-based morphisms been explicitly used in SE?	• An initial belief was that there currently exists only (or largely) implicit use of morphisms in the discipline and practice of SE. For example, the descriptive definition of a verification model as having medium-fidelity compared to the final product is an unconfirmed, heuristic assumption that implicitly describes a morphism. • This question targets documentation of explicit use of systems theory-based morphisms. The meaning of explicit here is that system specifications are defined in the form of mathematical (algebraic) structures for open, discrete, deterministic system; and, mathematical definition of equivalence between pairs of structures is defined.

2.2.2 Taxonomy of Key words

Key words are defined along with justification in Table 3. These should be considered the initial set of key words used to start the literature review. Other key words may have been identified in the process and subsequently used, which is not recorded here. For example, the use of [word in brackets] shows some extensions of the taxonomy. Using the first set of key words as an example, the following was searched “problem space of function,” “problem space of function for requirements,” “problem space of function for system requirements,” and “problem space of function for verification requirements.”

Table 3: Key Words Used for the Literature Search

Key Words	Justification
Problem space of functions [for] [requirements, system requirements, verification requirements]	This served to capture the use of problem spaces of functions in SE and to establish an understanding of how verification requirements are characterized relative to system requirements.
[System] [equivalence, fidelity, pedigree]	This served to confirm belief that minimal work has been completed in SE to determine system equivalence (or fidelity, or pedigree) mathematically.
Morphism [systems theory]	This served to capture general research that leveraged morphisms. Specific focus will be given to articles that indicate toward verification. The results will establish an understanding of how morphisms have been used relative to the proposed research for this dissertation.
Homomorphism [systems theory]	The main morphism that will be leveraged in this research is a homomorphism. In fact, a parameter morphism is an approximate homomorphism. From this, it serves to focus the search on use of homomorphism for verification. The results established an understanding of how homomorphism has been used relative to the proposed research for this dissertation.
Verification [requirement, model]	This served capture general research related to verification, with emphasis on definition of verification requirements and verification models.

Verification model relationship to [system requirements, verification requirements, system design]	This served to capture the relationships between verification models with system requirements, verification requirements, and system designs. The specific focus was on systems theory-based relationships.

2.2.3 Target Sources

While relevant research is possible to be discovered in other venues; the highest priority is given to the INCOSE sponsored research (Wiley), which provides the largest centralized knowledge of the state of SE practice. For example, the Conference on Systems Engineering Research (CSER) has yet to centralize all of its publications; however, sources that are known to publish CSER articles were also targeted. For example, the Procedia Computer Science has published many CSER articles, which is part of the Science Direct (Elsevier) database. The assumption for this literature review is that an indication of relevant research should exist, if at all, within INCOSE sponsored research and other venues will have limited insights; which is confirmed through screening of all venues referenced in Table 4. Other venues may have been identified in the process and subsequently used, which were not recorded here.

The target venues were leverages as follows: The use of [word in brackets] shows some extensions or refinement of the venue search. For example, there was a general search of Wiley and a specific search of the Wiley SE journal.

Table 4: Venues Targeted for the Literature Search

Target Venues	Justification
Wiley [SE, INSIGHT, and INCOSE-IS]	These are the publication venues for INCOSE, which suggests that a large percentage of SE sponsored research will be covered in these venues. A general search of Wiley will be conducted based on initial screening of article titles.
IEEE [Systems, SysCon]	This is considered to be a main source of publication for SE sponsored research. A general search of IEEE will be conducted based on initial screening of article titles.
Springer	This is considered to cover many of the publications from the Conference on Systems Engineering Research (CSER), which were published in book form. A general search of Springer will be conducted based on initial screening of article titles.
Science Direct (Elsevier) [Procedia Computer Science]	This is considered to cover many of the publications from the Conference on Systems Engineering Research (CSER). A general search of Science Direct will be conducted based on initial screening of article titles.
AIAA	A general search of AIAA will be conducted based on initial screening of article titles.
MDPI [Systems]	This venue has recently been gaining thrust as a publication venue for SE research.

2.3 Literature Review Results

Overall, the literature review was consistent with a recent survey of INCOSE sponsored publications, which found a lack of research on verification [43]. Additionally, the literature suggests that a common belief exists that verification models only need to represent the system design “as far as required for test purposes” and representativeness largely remains a qualitative definition (e.g., high-, medium-, low-) [42]. Verification models may include, as examples, mockup, development models, breadboards, integration models, structural models, thermal models, engineering models, qualification or certification models, and operational models [42]. A breadboard, as an example, may only account for limited functional and almost no physical resemblance to the design. The intention, in the case of the breadboard, is to perform an activity to verify specific, required functionality of the real system to which the breadboard is a surrogate and, thus, infer knowledge as to probable adherence of the system design to corresponding system requirements. Essentially, there is an orthogonality assumption that allows to infer knowledge from parts of the system, which are thought to not affect other aspects of the system.

2.3.1 Relationships to verification models

The literature review provided context of relationships to verification models that was largely consistent with the use of SysML as discussed in [3, 45] for descriptive relationships and the collection of SE expertise discussed in [42] for textual relationships. In SysML, the “requirement” element serves the purpose of defining the system requirements as blocks of text. From the “requirement” element a “verify” relationship is drawn to the “test case” element, which serves the purposes of a verification requirement and/or verification model. From a verification requirement and verification model perspective, the “test case” may define a set of verification activities; however, no specification of desired representativeness of the verification model to the system design is inherent to the “test case” element. Furthermore, no inherent relationship is defined in SysML between the “test case” element and the system design “block” element. As for textual relationships, the table on page 413 of [42] suggests a textual verification requirement should define a function or quality to be verified, presumably from a specification in the system requirements and that fidelity of the verification model should be defined “if applicable,” which suggest that definition of fidelity is optional. Neither the descriptive relationships in SysML nor the textual relationships in [42] are mathematically based. From observations of the above, a particular item of note is the lack of inherent or mandatory specification of fidelity of a verification model; which suggests that representativeness of verification models to system designs is minimally considered and largely limited to implicit consideration by the discipline and practice of SE and, therefore, a research gap may exist.

Two major bodies of research were discovered in review of mathematical relationships, one of which is the verifiable design process (VDP) [46-50]. The process leverages category theory to relate requirements written in natural language to requirements in ontology form, requirements in ontology form to logical/mathematical representation of a system, logical/mathematical representation of a system to theory/proof based on the logical representation, logical/mathematical representation of a system to a system of interconnected models, and a system of interconnected models to simulations. Although verification is implied with the name VDP, the intent of VDP is expressly stated as a design process used to validate adherence to stakeholder needs through simulation of models. This suggests that the notion of verification and a verification model is not included in the research. Furthermore, the validation model has a relationship to the system design and an indirect relationship to the requirements through the system design. Lastly, there are no explicit mathematical structures defined for the (stakeholder needs) requirements, system design, or validation model; rather, VDP essentially defines a validation process flow between these “categories" that presumably may be defined by any number of mathematical structures. In addition to the lack of definite mathematical structures, the lack of focus on verification further suggests existence of a research gap.

The other major body of research with mathematical relationships is that of Wymorian systems theory, specifically T3SD [23, 44]. Comparable to the term verification requirement used for this dissertation, the system test requirement of T3SD is defined through a subset of the system requirements. The verification activity is conducted on a system design model, which is inferred to adhere to the system requirements through a relationship to a more abstract system design model. An implication here is that the system design (note, the more elaborate system design) is the subject of the verification activity rather than an abstract verification model that is representative of the system design. In other words, the verification model in T3SD is the system design in the sense used in this dissertation. Despite the claim by Wymore that T3SD is a framework for verification [51], the lack of a notion of verification model as an abstract representation of a system design that is used for the verification activity suggests otherwise. However, T3SD does have clearly defined mathematical structures and mathematical relationships between the structures, for which many are captured in the Appendix (7.2.1); and which suggests there is research to ground this dissertation.

2.3.2 Problem spaces of functions

The only discovered research body that defines requirements as problem spaces of functions is Wymorian systems theory, specifically the True Model-Based Requirements (TMBR) methodology [40, 52-57]. The TMBR method suggests that all requirements may be defined as desired transformations of inputs into outputs through desired interfaces. The problem space of functions defines the conditions that bound a solution space, which is a set of system designs that adhere to the conditions. Note, the use of the term requirement is distinct from (stakeholder) needs, which is a problem space of outcomes [38] and is relevant to validation rather than verification. However, the use of the term requirement with TMBR is not limited to system requirements and has been suggested to be extended to include aspects of verification requirements [53].

A member of the Wymorian systems theory family and close relative to a problem space of functions is the mathematical structure named the input/output function (IOFO) of the discrete event system specification (DEVS) framework [44, 58]. Models of systems may be specified on the basis of the IOFO and proven to adhere to the IOFO. Additionally, DEVS has been proposed to be merged with MBSE [6, 59], conjoined with T3SD [44], and used as the basis for verification [60]; which suggests that DEVS provides foundations to ground this dissertation research. Further documentation on DEVS is provided in the Appendix (7.2.2).

2.3.3 Systems theory-based morphisms

Overall, the use of morphisms in the literature is largely limited to documentation of explicit use of morphism-based terms and vague sense of meaning, rather than being provided with mathematical rigor. For examples, the use of "self-morphing systems" [61]; "morphable architecture" [62]; homomorphism [63, 64]; and "graph morphisms," "concept morphisms," and "infomorphism" [65] are all examples of use of morphic-based terms without providing a mathematical context and none of which are using morphisms to determine equivalence between problem spaces of functions and between verification models and system designs as was used for this dissertation. However, the literature review discovered one article that leveraged the use of the morphic term homeomorphism as a means to determine equivalence between topological spaces [66]; and, although it is relevant to determining equivalence between problem spaces of functions, the article did not provide mathematical rigor. This suggests that the use of morphisms largely remains as implicit, heuristic assumptions for the discipline and practice of SE; and that there exists a research gap.

Some research articles that did provide mathematical rigor are the VDP, which was discussed previously, and that found in [67]. Both of the research bodies are based on the use of category theory. In the latter, the article discussed the transformations of construction and deconstructions that systems undergo throughout the system lifecycle. This type of research is considered to be relevant to this dissertation in that real engineered systems have a dynamic relationship between requirements, design, and verification; however, this type of research is deferred for future research because only static relationships are considered necessary to address the dissertation research question. Furthermore, there is no indication in [67] that the models are based on systems theory, meaning that the article does not define a systems theoretic mathematical structure that may be leveraged to define, as an example, system designs and verification models as well their morphic equivalence.

The use of systems theoretic morphisms is a foundational principal of Wymorian systems theory (e.g., [44]). As an example, T3SD leverages homomorphism to determine the equivalence, discussed previously, between a more abstract and more elaborate system design; which are based on rich mathematical definition. However, T3SD only includes morphisms at one level of system specification. The term system specification is used here to mean a systems theoretic mathematical structure as is consistent with usage in literature on DEVS, which includes the hierarchy of system specification and associated morphisms at each level in the hierarchy. Simplification of the T3SD and DEVS hierarchy of system specification is shown in Figure 1. In the comparison, T3SD only has morphisms at one level (red horizontal arrow) and DEVS has multi-level morphisms (three horizontal arrows). The two grey circles around the morphism arrows for DEVS show the morphisms that are not included in T3SD; where the morphism used by T3SD is equivalent to the morphism at the IO System level for DEVS.

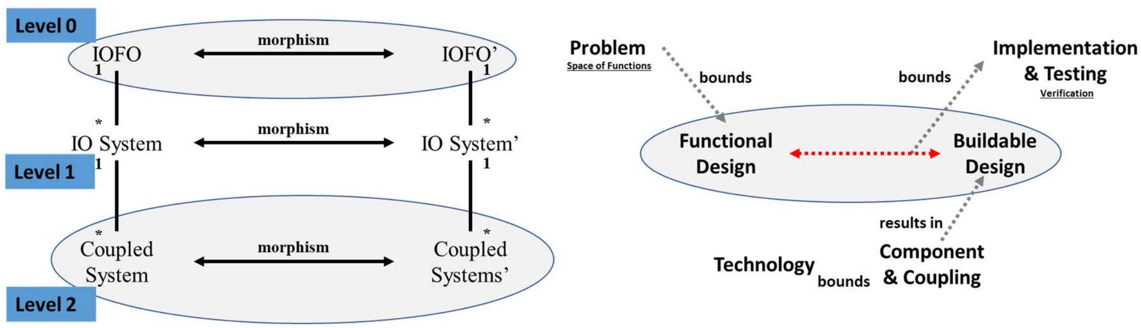

Figure 1: Summary metamodels of the DEVS and T3SD branches of Wymorian systems theories

DEVS includes the input/output function (IOFO), input/output system (IO System), and network of systems (component coupled system). Each level in the hierarchy, from Level 0 to Level 2 in this case, defines increasing detail in the mathematical structure of the system specification. While the mathematical hierarchy provides means of a recursive elaboration and abstraction in a stratification, the morphisms provide means for understanding of equivalence through iterative elaboration and abstraction. Research has proposed a conjoining of T3SD and DEVS [44]; suggesting that the IOFO of DEVS is equivalent to the problem space of functions in T3SD, the IO System is equivalent to the system models defined for the functional design of T3SD, and the network of systems (coupled system) of DEVS is equivalent to the component coupling of T3SD. Further detail on the Wymorian systems theories, T3SD and DEVS, is provided in the Appendix (7.2); which provide the foundations for this dissertation.

Mesarovician systems theory, originating from [20, 21], also leverages systems theoretic morphisms. Recent research has suggested revitalized application of Mesarovician systems theory and some convergence with the SE domain [68-71]. Of particular interest to this dissertation research is that found in [71]. The research suggests that morphisms can be used to characterize the relationship between a "prototype" (i.e., verification model) and corresponding system design, which is part of what is necessary to address the research question in this dissertation. Here, the prototype is a verification model that is an abstract representation of the system design; which is used to infer knowledge about the adherence of the system design to system requirements through assumed orthogonality. However, the body of research does not appear to characterize the assumption of orthogonality, which is necessary to address the research question in this dissertation. Furthermore, as is suggested in [68], Mesarovician systems theory was created to mathematically characterize general systems; whereas Wymorian systems theory was created to mathematically characterize engineered system, which suggests that Wymorian systems theory provides a stronger case as a foundation for addressing the research question in this dissertation.

3 Research Methodology

3.1 Summary of research tasks

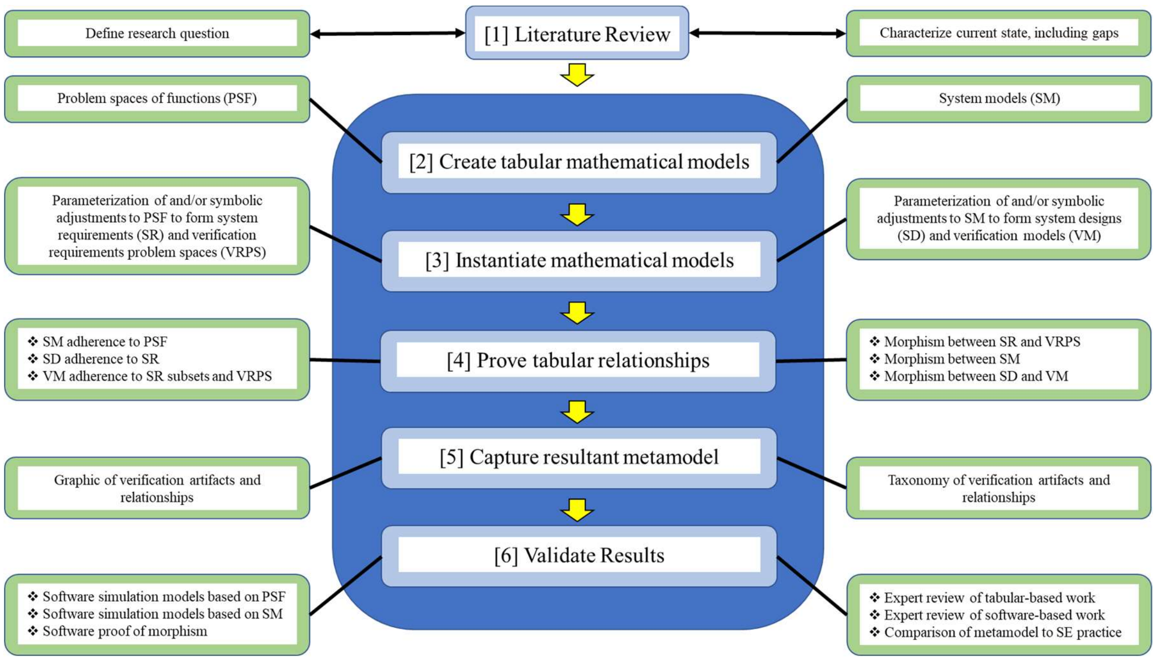

Figure 2: Visual summary of research tasks

This chapter provides detailed explanation of the methods used to complete the research tasks, which is summarized visually in Figure 2. The literature review informed all activities with specific emphasis on leveraging theoretical foundations from Wymorian systems theory (e.g., [44]). Although other theoretical bodies of research exist with potential, Wymorian systems theory has the pieces necessary to address the research question. Specifically, Wymorian systems theory includes theoretical foundations for problem spaces of functions (PSF) (e.g., [40, 53]), which are used to characterize system requirements (SR) and aspects of verification requirements referred to as verification requirement problem spaces (VRPS); morphisms (e.g., [53, 72]), which are used to characterized equivalence between SR and VRPS as well as between system designs (SD) and verification models (VM); and hierarchy of system specification (e.g., [44]), which is used as a basis to characterize hierarchy of detail from SR and VRPS to varying detail of SD and VM structure.

This dissertation has selected to focus on open, discrete, deterministic systems to address the research question. From a Wymorian systems theory perspective, an open system is a transformation of inputs to outputs through interfaces. Both T3SD and DEVS provide mathematical structures for defining open, discrete, deterministic systems and corresponding PSF; which are leveraged throughout this dissertation. Furthermore, the SR are based on the simple desires for the SD to:

1. Provide yellow light only when commanded and
2. Be water-resistant

The remainder of this section is as follows: First, a taxonomy stemming from the literature review is defined. Second, mathematical structures based on Wymorian systems theory are defined in tabular form to serve as PSF and system models (SM). Note, from a systems theory perspective, the notion of system is independent of context (i.e., domain); which suggests that mathematical structures may be instantiated to add the context. Therefore, third, the mathematical structures for the PSF are parameterized to form SR as well as VRPS and the mathematical structures for the SM are parameterized to form SD as well as VM. Fourth, tabular relationships were proven for SM adherence to PSF, SD adherence to SR, VM adherence to SR, VM adherence to SR subsets, VM adherence to VRPS, morphisms between SR and VRPS, morphisms between SM, and morphisms between SD and VM. Fifth, a metamodel was established on the basis of the exploration of the relationships between verification artifacts. Sixth, all research was validated including simulation of the PSF, simulation of the SM, software proof of SM morphisms, expert review of the tabular results, expert review of software-based validation, and, finally, the metamodel of verification artifacts was compared to SE practice to validate uniqueness of the results.

Note, some of the steps defined above are captured as part of the methods chapter below and other steps are considered to be results and, therefore captured in the results chapter. The tabular mathematical structures from step two and instantiation of mathematical structures are provided in the methods chapter below. Proof of tabular relationships, the metamodel, and validation are considered to be part of the results; however, the methods are discussed in this chapter.

3.1.1 Taxonomy

This section provides the taxonomy of general terms used for this dissertation. Further detail, such as mathematical (algebraic) structures, are defined in later sections of the methodology where further specificity of meaning is necessary.

The overall taxonomy stems from the literature review and a desire to be grounded on the basis of Wymorian systems theory. Therefore, the taxonomy and methods are based in both T3SD and DEVS. The tabular mathematical models are largely based on T3SD, which provides relatively simple mathematical structures. However, T3SD only views morphisms at a singular level of system specification; and, alternatively, DEVS provides the basis for a hierarchy of morphisms between levels of system specification. Here the term system specification is used, consistent with DEVS, in reference to mathematical structures within a hierarchy of increasing (or decreasing) levels of system structure, which is explained in further detail in the remainder of this section. Additionally, both T3SD and DEVS are grounded on the notion of a Moore-state machine, which provides a basis for comparison between the two. Furthermore, DEVS has computational software implementation, which enables validation of the tabular results.

3.1.1.1 Hierarchy of system specification

Consistent with the DEVS notion of a hierarchy of system specification, this dissertation defines three levels at which system specifications are defined, which are shown in Table

5 below. Note, system specifications are algebraic structures for defining increasing knowledge of system structure consistent with systems theory.

Table 5: Description of the hierarchy of mathematical specification

Level	Description
Level 0 *(L0)* *Also referred to as* ***Problem Space of Functions (PSF)***	• *defines external structure such as input/output (IO) items of exchange (IoX), interfaces (IFs), IoX transformation functions. Examples of algebraic structures at L0 include the IOR from T3SD as well as the IO observation frame, IORO, and IOFO from DEVS. Note, in the case of DEVS, this is a simplification for translation from a M&S paradigm to a SE paradigm. Furthermore, system specification models consistent with TMBR are considered to be specified at L0.* • Level at which problem spaces of functions are defined • Note, the selection here of L0 and IOFO as the basis for the problem space of functions (and associate morphism) is a simplification assumption. The term space stems from topology, which is a field of mathematics considered to be out of scope for this dissertation. The results are not expected to vary based on this assumption; however, future research should consider topology (and associated morphisms).
Level 1 *(L1)* *Also referred to as* ***System Model***	• *defines external structure such as inputs/outputs (IO) items of exchange (IoX), interfaces (IFs), conditions of applicability, as well as defines the internal structure as a state machine that characterizes the global behavior. Examples of algebraic structures at L1 include the FSD, Z, Z@, and ZS from T3SD as well as the IO System from DEVS. Note, the resultant of the coupling of components (Z@) in T3SD is modeled at L1, which is consistent with the implementation in this dissertation. Note, in the case of DEVS, this is a simplification for translation from a M&S paradigm to a SE paradigm.* • Least detailed level of interior structure at which system designs and verification models are defined
Level 2 *(L2)* *Also referred to as* ***System Model***	• *defines both external and internal structure as inputs/outputs (IO) items of exchange (IoX), interfaces (IFs), conditions of applicability, as well as defines the internal structure of components as state machines that characterize component behavior. Examples of algebraic structures at L2 include the SCR from T3SD as well as the Network of Systems (Component Coupled System) from DEVS. Note, in the case of DEVS, this is a simplification for translation from a M&S paradigm to a SE paradigm.* • Most detailed level of interior structure at which system designs and verification models are defined

A simplification made above in description of L0, L1, and L2 is the use of the term *item of exchange* (IoX); which may be used interchangeably with *input/output* (IO). Specifically, this is intended to simplify the description at L2, which from a DEVS and T3SD perspective would require repeating information when the IoX is an output of one component and an input to another component. The idea here is that the item does not change; rather, the relationships are added or removed as the item is exchanged with an output relationship to the providing component system and with an input relationship to receiving component system. Note, DEVS uses the term interface in reference to IO ports, which is used for simulation purposes and defines a single port for every IO. This dissertation assumes that interfaces may transfer multiple IoX/IO and that the interfaces are transparent to IoX.

All system specifications at L1 and components at L2 include state machines, which are defined in Table 6. Furthermore, a system specification at L1 and components specification L2 are also defined as a minimum system model (sometimes referred to as an atomic model [73]). The minimum system model has a minimum number of states and, therefore, transitions; which enhances the ability to both couple system models to form the emergent behavior and to more readily discover morphic equivalence. All state machines have been selected and created as minimum system models, which can be readily observed due to the fact that each output is assigned to only one state and occurs only once. A specific assumption here is in regard to the minimization of the resultant of coupled system models. The resultant of coupled system models initially has a number of states resulting from the cross product of the states of each component system model. In the cases for this dissertation, the initial number of states prior to minimization would be nine states and four states, which were minimized to three states and two states. The minimum system models were validated through subject matter expert review. The terms state machine and minimum system model are further defined in Table 6 below.

Table 6: Description of state-based items used for this dissertation

Item	Description
State machines	• *characterize the IO/IoX, IO/IoX trajectories, states, and state trajectories as well as being closed under concatenation* [73]. *This means that the state machine provides a holistic system function, rather than functions of the system such as is present with the IOFO in the DEVS formalism. Furthermore, the state machines referenced in this research are considered to be based on the Moore-type state machine (e.g.,* [74]*); which, although is consistent with both T3SD and DEVS, state machines shown in tabular form in this dissertation will be consistent with T3SD.*
Minimum system models	• *are state machines that characterize the behavior and structure through the minimal set of states, IO/IoX, and transitions* [75].

3.1.1.2 Morphisms

This dissertation has selected several morphisms to serve as the basis for this research. This selection of morphisms is not intended to be comprehensive; rather, the list is a starting point from which future research may expand. Note, this dissertation distinguishes between equality and equivalence. Using the example of a well-known morphism between a mechanical spring and electric circuit (e.g., [71]); there is equivalence between the mechanical spring and electric circuit, and, whereas there may be equality between two mechanical springs or between two electric circuits. The term equivalence is intended to mean commonality in underlying mathematical structure such as to precisely characterize abstraction and elaboration, such as a mechanical spring to electric circuit or mechanical spring to another mechanical spring specified at a different (iterative) abstraction/elaboration. Whereas, the term equal is intended to mean exact underlying mathematical structure at the same (iterative) abstraction and with the same instantiation, such as two mechanical springs specified at the same (iterative) abstraction/elaboration. Note, a morphism that demonstrates equality is also equivalent. Furthermore, the basis of this research on T3SD and DEVS enables usage of their morphic proof and validation software (MS4 Me [76]) in this body of research. Morphic proof is provided in tabular form through mapping IoX and corresponding parameters, where applicable; IF and corresponding parameters, where applicable; and other structure such as IO function in the case of PSF as well as states, next state, readout functions, and coupling functions in the case of SM. Further detail is provided in the later sections. The categories of morphisms selected for this dissertation are considered to be an initial set and not intended to be comprehensive of all existing or possible system morphisms, which is left for future research. The morphisms select are provided and described in Table 7, which also includes simplifications applied to this dissertation and notional examples.

Table 7: Description of morphisms selected for use in this research

Morphism	Description	Notional Example
Homomorphism (hom)	• A mapping of the preservation of equivalence between a pair of system specifications of the same algebraic structure • May be bijective, surjective, or injective • For this dissertation, all morphisms are considered to be bijective in the tabular form. However, the validation algorithm requires a surjective approach. This is a non-issue due to the simplicity of the specifications, which are readily proven to have bijective morphisms and is inherent to	• One mechanical spring to another mechanical spring

	the tabular proof provided (i.e., the tables would not change content or outcome).	
Isomorphism (iso)	• Is a homomorphism with a one-to-one mapping	• Mechanical spring to electric circuit
Identity isomorphism (ids)	• Is an isomorphism with equality mapping in underlying mathematical structure and instantiated parameter space	• The same mechanical spring to the same mechanical spring
Parameter morphism (par)	• A mapping of the preservation of equivalence between parameters spaces of a pair of system specifications • Note: For this dissertation, parameters are considered to be associated with the values and/or units of IoX and IF	• Parameters of the mechanical spring to parameters of the electric circuit
Identity parameter morphism (idp)	• Is a parameter morphism with an equality between parameter values and units	• Parameters of a mechanical spring to parameters same (or potentially another) mechanical spring
L0 morphism *Also referred to as* ***Problem space of functions (PFS) morphism***	• Morphism that occurs at the external structure of system specification such as between IoX, IF, functions, and associated parameters • Note: For this dissertation, the L0 morphism is considered to be function-based similar to the IOR of T3SD and IOFO of DEVS, which is the basis for the problem spaces of functions used in this dissertation • An ids at L0 has a one-to-one mapping between IoX, IF, and IoX transformation functions with a corresponding idp • An iso at L0 has a one-to-one mapping between IoX, IF, and IoX transformation functions with allowable par • A hom at L0 has a one-to-one or one-to-many mapping between IoX, IF,	• Problem space for a mechanical spring to a space of an electric circuit

	and IoX transformation functions with allowable par	
L1 morphism	• Morphism that occurs at the system state and transition level; which includes external structure such as between IoX, IF, functions, and associated parameters as well the internal structure of system states and state transition; however, this does not include the internal structure defining of components, component states, component state transitions, or internal IoX and IF. • Note: For this dissertation, the L1 morphism is considered to be state-based similar to Z, FSD, and Z@ of T3SD as well as the IO System of DEVS • An ids at L1 has a one-to-one mapping between IoX, IF, and states with a corresponding idp • An iso at L1 has a one-to-one mapping between IoX, IF, and states with allowable par • A hom at L1 has a one-to-one or one-to-many mapping between IoX, IF, and states with allowable par	• Mechanical spring to an electric circuit or another mechanical spring
L2 morphism	• Morphism that includes the external and internal structure of system specification such as between IoX, IF, functions, and associated parameters as well as components and their states • Morphism that; in addition to including external int interface of system specification such as between IoX, IF, functions, and associated parameters; includes states at the global level of a system specification relative to itself without representation of internal component structure • Note: For this dissertation, the L2 morphism is considered to be largely state-based (on components) similar to SCR of T3SD as well as the Network of Systems of DEVS	• Components and coupling of a mechanical spring to the components and coupling of an electric circuit or another mechanical spring

	• An ids at L0 has a one-to-one mapping between IoX, IF, states, and components with a corresponding idp • An iso at L0 has a one-to-one mapping between IoX, IF, states, and components with allowable par • A hom at L0 has a one-to-one or one-to-many mapping between IoX, IF, states, and components with allowable par • Note: A special case is the hom with idp, which is used for this dissertation for exact equivalence between internal IF of a pair of system specifications	

3.2 Tabular mathematical structures

3.2.1 Problem spaces of functions

For problem spaces of functions, a modified version of the DEVS IOFO was selected. The two categories of problem spaces of functions in this body of research are system requirement problem spaces and verification requirement problem spaces. Each problem space is characterized through the following mathematical expression:

$$PSF = (X, Y, XY, P, F) \tag{1}$$

Where PSF is the problem space of functions, X is the required set of input IoX, Y is the required set of output IoX, XY is the required set of IoX transformation functions, P is the required set of physical interfaces, F is the interface mapping function that maps the required IoX to required interfaces.

Furthermore, the PSF are represented as block diagrams to visualize P, the interface mapping function, and as sequence diagrams to visualize XY, the IoX transformation functions.

For this dissertation, seven PSF have been defined, which is the number necessary to characterize SR for a light-providing device that is water-resistant and of which six are a subset of a superset referred to as PSF_S1. The superset provides the underlying mathematical structure of the entire SR. Subsets of PSF serve as the basis for exploration of the potential limitation of definition of VM based on direct relationship to SR and heuristic assumption of perceived orthogonality in SR subsets. Subsets of PSF also serve as the basis for the underlying mathematical structure of the VRPS, which are selected due to known orthogonality in the SD. The use of PSF as subsets of a superset of PSF enables inherent morphic equivalence determination from the subsets to the superset. Last, the SR and VRPS are parameterizations of the PSF.

Furthermore, the PSF provide part of the foundation for characterization of morphic conditions between SM, and subsequently between SD and VM. Each PSF defines the IO function (XY), which serves as a reference point for defining the deserved equivalence (morphic conditions). This is explained in further detail in the section on verification requirement morphic conditions (VMMC).

The PSF provide a basis for validating the SM. The notion of an experimental frame is leveraged from DEVS. The PSF provide the IO and IO trajectories, which are sampled in the MS4 Me software. Further detail is provided in the validation section of the methods chapter.

An example PSF is shown in Table 8 and Figure 3. The table defines the tabular mathematical structure, which are visual shown in the figure as a block diagram representing the desired IoX inputs to be transformed to IoX outputs through desired IF and a sequence diagram (e.g., [3, 45]) representing the transformation function.

Table 8: Example tabular mathematical specification of a problem space of functions

PSF_1	(X_1, Y_1, XY_1, F_1, P_1)
X_1	{IoX_1}
Y_1	{IoX_2}
XY_1	{XY-1}; where, XY-1 = (IoX_1, IoX_2)
F_1	{IF-1, IF-2}
P_1	{(IoX_1, IF-1), (IoX_2, IF-2)}

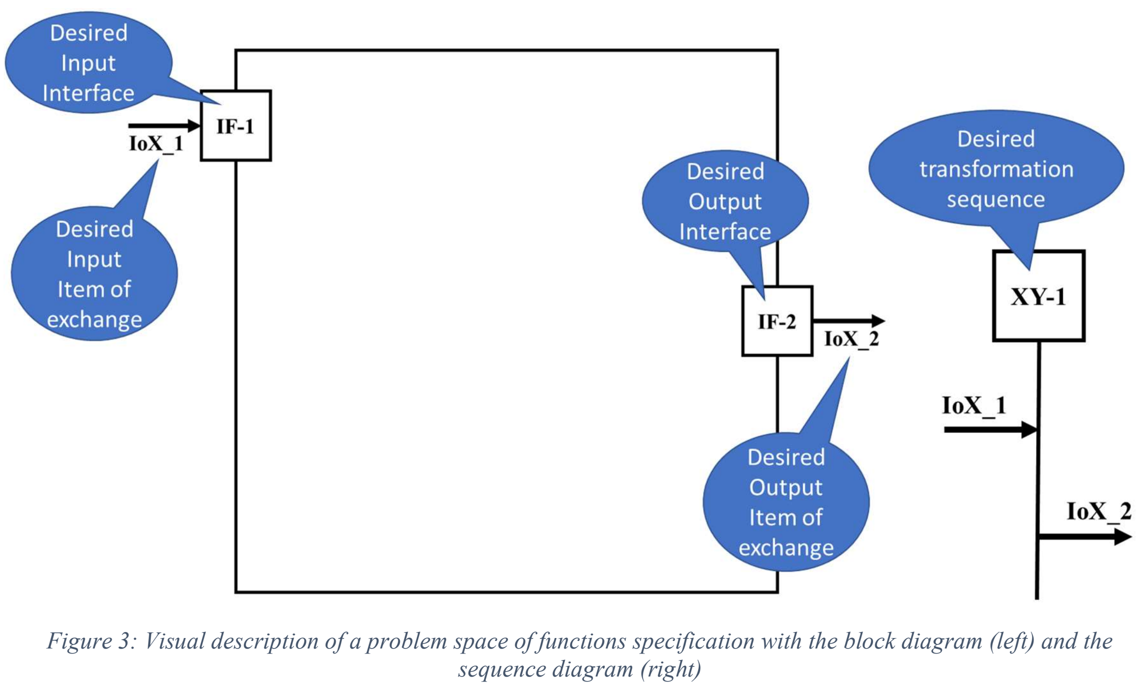

Figure 3: Visual description of a problem space of functions specification with the block diagram (left) and the sequence diagram (right)

The full set of PSF are defined in the Appendix (7.4).

3.2.2 System Models

This section defines the system models through visual aid paired with the modified T3SD mathematical perspective.

Block diagrams are used for visual aid to show the mapping of IoX to physical interfaces, assign IoX as relationships to the system model in terms of input/output directional arrows, and define the coupling of component systems. The state machines are represented in accordance with Moore-based state machines where the state shown in the top half of the circle, the output is shown in the bottom half of the circle, and the inputs are shown as arrows from the state at which the input is received and to the state being transitioned to.

The modified T3SD mathematical expression of a L1 system specification is defined as follows:

$$Z = (S, X, Y, N, R, P, F) \tag{2}$$

Where Z is the L1 system specification, S is the set of system states, X is the set of input IoX, Y is the set of output IoX, N is the next state function that characterizes the transition between states based on receipt of X, R is the readout function that maps the states and outputs, P is the set of physical interfaces, and F is the interfacing input mapping function.

The modified T3SD mathematical expression of a L2 system specification is defined through the follow set of equations:

$$B = (SCR, Z@) \tag{3}$$

Where B is the combination of the set of component coupling recipes SCR characterized at L2 and the resultant system model Z@ characterized at L1 in accordance with Z. Each SCR is modified from T3SD to form the equation below:

$$SCR_i = \{(VZ_i, VF_i)\} \tag{4}$$

Where SCR is the component coupling recipe, VZ is the vector of system models to be coupled with each system model defined in accordance with Z, and VF is the interface-IoX mapping functions. The following example of SCR is provided for further explanation:

$$SCR_1 = (VZ_1, VF_1) \tag{5}$$

$$VZ_1 = (Z_1, Z_2) \tag{6}$$

$$VF_1 = (IoX_1, IF_1) \tag{7}$$

Where SCR_1 is the first component coupling recipe within a set of component coupling recipes; VZ_1 is the vector of system models to be coupled in SCR_1, VF_1 is the set of interface-IoX mapping for coupling in SCR_1, can be read as Z_1 provides an output of IoX_1 as an input to Z_2 through IF_1, and may also be written as:

$$SCR_1 = \left((Z_1, Z_2), (IoX_1, IF_1)\right) \tag{8}$$

For the remainder of this section, descriptions of thirteen system models are defined. The thirteen system models were intentionally selected and defined as one, two, and three state system models with some having simultaneous IO/IoX and some being defined intentionally to serve as components to be coupled. The SR, VRPS, SD, VM are consistently defined as to level of detail and complexity. This level of detail and complexity is sufficient to meaningfully address the research question. Each subsection provides the mathematical description, block diagram to visualize the set of interfaces (P) as well as the interface mapping function (F), and a Moore-based state machine diagram.

For an example of a L1 system specification model, ZA is provided. Table 9 provides the mathematical description and Figure 4 provides a block diagram with a Moore-based state machine as a visual representation of the mathematical description.

Table 9: Example level 1 (L1) tabular mathematical specification of a system model

Z_A	(S_A, X_A, Y_A, N_A, R_A, F_A, P_A)
S_A	{S_A1, S_A2}
X_A	{IoX_A1, IoX_A2}
Y_A	{IoX_A3, IoX_A4}
N_A	{((S_A1, IoX_A1), S_A1), ((S_A1, IoX_A2), S_A2), ((S_A2, IoX_A1), S_A1), ((S_A2, IoX_A2), S_A2)}
R_A	{(S_A1, IoX_A3), (S_A2, IoX_A4)}
F_A	{IF-A1, IF-A2}
P_A	{(IoX_A1, IF-A1), (IoX_2, IF-A1), (IoX_A3, IF-A2), (IoX_A4, IF-A2)}

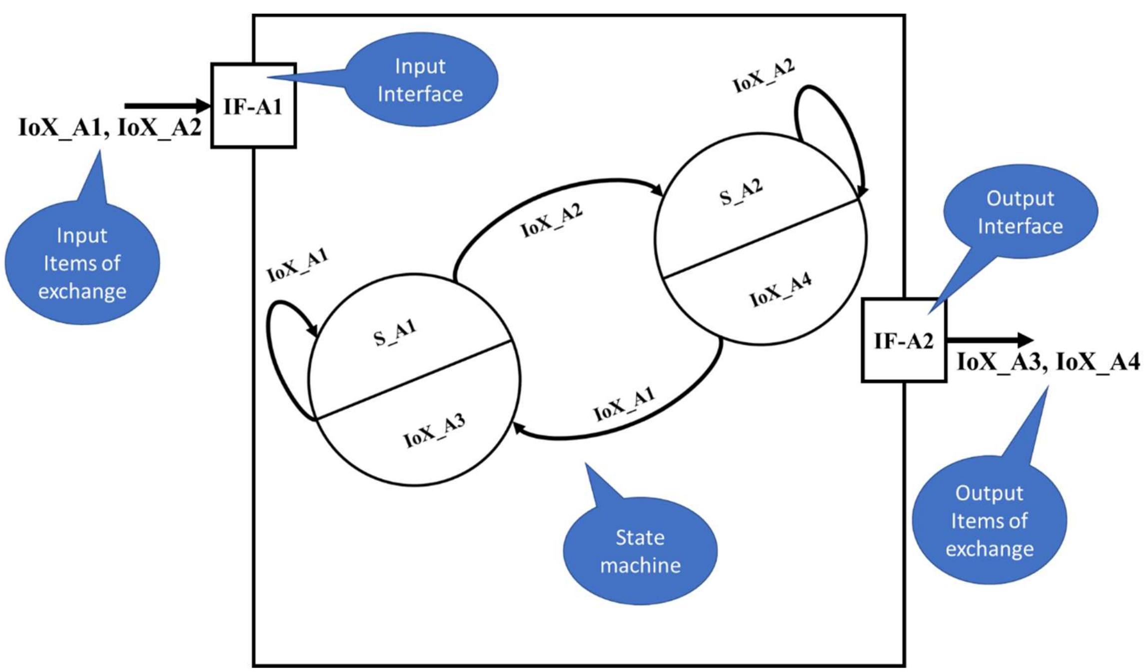

Figure 4: Visual description of a system model specification

Furthermore, Figure 5 is provided to visually explain L2 system model specifications and the resultant L1 system model specification.

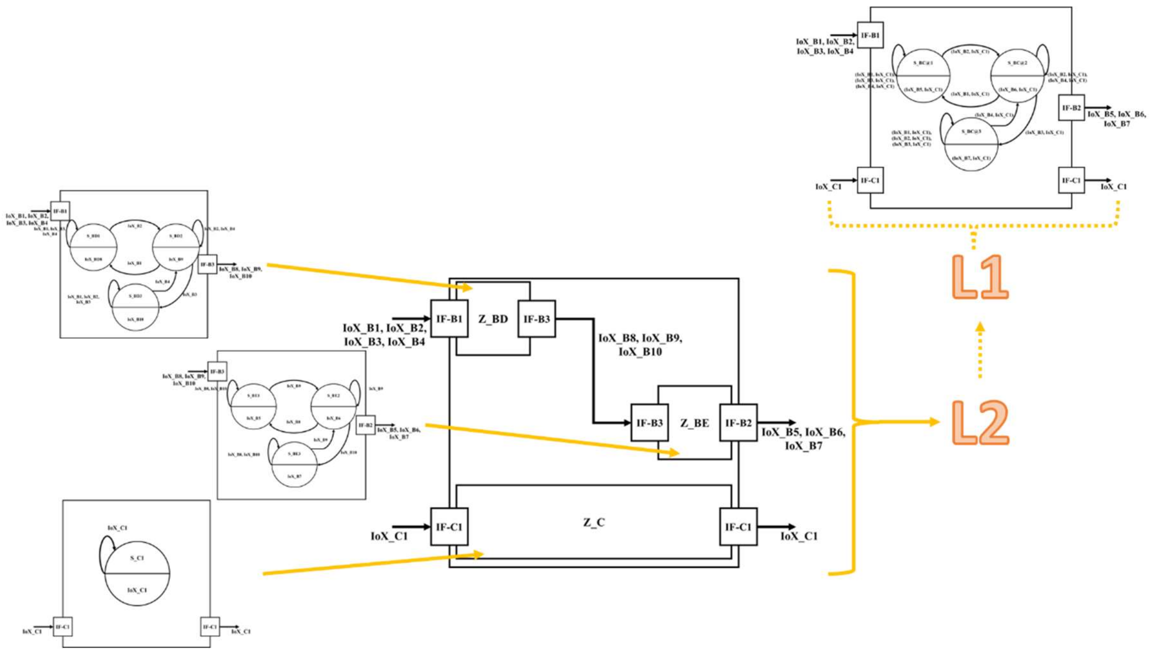

Figure 5: Visual description of a level 2 (L2) system model specification and resultant level 1 (L1) system model specification

The full set of SM are defined in the Appendix (7.5).

3.3 Instantiated mathematical models

3.3.1 Selection of System Requirement PSF

The superset SR is shown in Table 10 for the textual format. In some case, the parameter space is undefined, which is labeled as N/A. The undefined parameter space is intended to open the design space, meaning a larger set of systems within the solution space that is bound by the problem space. For example, there is not a parameter set defined for the on/off command interfaces and IoXs, which allows flexibility in design of the engineered system.

Table 10: Textual system requirements defined for the desire system of interest

ID#	Description
SR1	The system shall accept an input of "off-command" through IF-1 • Note: IF-1 has undefined parameters to open the design space • Note: The off-command has undefined parameters to open the design space
SR2	The system shall accept an input of "on-command" through IF-1 • Note: IF-1 has undefined parameters to open the design space • Note: The on-command has undefined parameters to open the design space
SR3	The system shall provide no-light after accepting the "off-command" through IF-2 • Note: IF-2 has undefined parameters to open the design space

	• Lumen: <0.5 lm
SR4	The system shall provide an output of light through IF-2 after accepting the "on-command": • Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm • Note: IF-2 has undefined parameters to open the design space
SR5	The system shall reject water through IF-3 according to the following standard: • Pressure: pressure within 1-5 atm • Humidity: 0-100% • Note: IF-3 has undefined parameters to open the design space

As stated previously, the superset of PSF serves as the underlying mathematical structure for the superset of SR, which is divided into subsets and mapped to the PSF in accordance with the three functions (XY-S1, XY-S2, XY-S3) and corresponding interfaces as well as pairing between them. This enables the exploration of verification model defined from system requirements by treating the system requirements as subsets as through an assumed existence of orthogonality.

The correspondence between PSF and SR is shown in Table 11, after which further definition of the SR in textual and model-based form is provided. For interpretation of the table, superset SR is an instantiation of the PSF_S1.

Table 11:Mapping of subsets of textual system requirements to subsets of problem spaces of functions

SR	PSF
Superset SR	PSF_S1 (XY-S1, XY-S2, XY-S3)
SR1 and SR3	PSF_S3 (XY-S1)
SR2 and SR4	PSF_S4 (XY-S2)
SR5	PSF_S7 (XY-S3)
SR1, SR3, SR5	PSF_S5 (XY-S1, XY-S3)
SR2, SR4, SR5	PSF_S6 (XY-S2, XY-S3)

The superset SR has a mathematical structure consistent with PSF_S1. The remainder of this section provides Table 12 for the instantiation of IoX, Table 13 for instantiation of interfaces (F), Figure 6 for the block diagram of interface to IoX mapping, Figure 7 for the sequence diagrams (e.g., [3, 45]) of IoX transformation functions.

Table 12: Item of exchange (IoX) Instantiation of a problem space of functions to form the system requirements

IoX ID	Descriptor	Parameterization
IoX_S1	Off-command	• N/A
IoX_S2	On-command	• N/A
IoX_S3	No-light	• Lumen: <0.5 lm
IoX_S4	Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm
IoX_S5	Water	• Pressure: 1-5 atm • Humidity: 0-100%

Table 13: Interface (IF) Instantiation of a problem space of functions to form the system requirements

IF ID	Descriptor	Parameterization
IF-S1	On/off IF	N/A
IF-S2	Light IF	N/A
IF-S3	Water IF	N/A

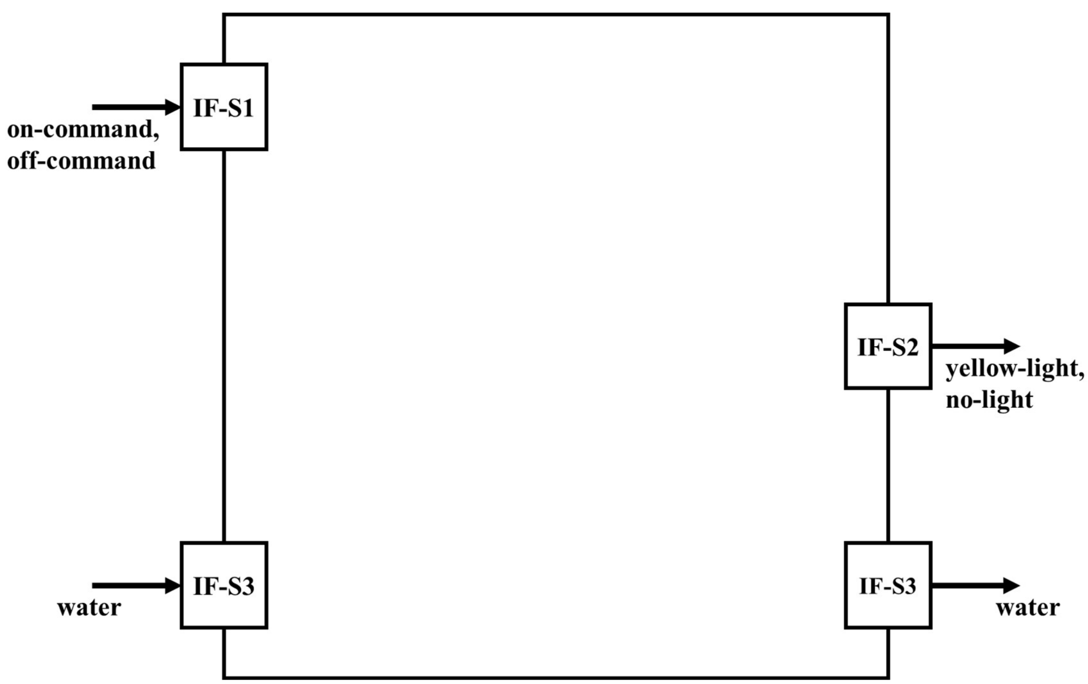

Figure 6: Block diagram description of the system requirements problem space of functions

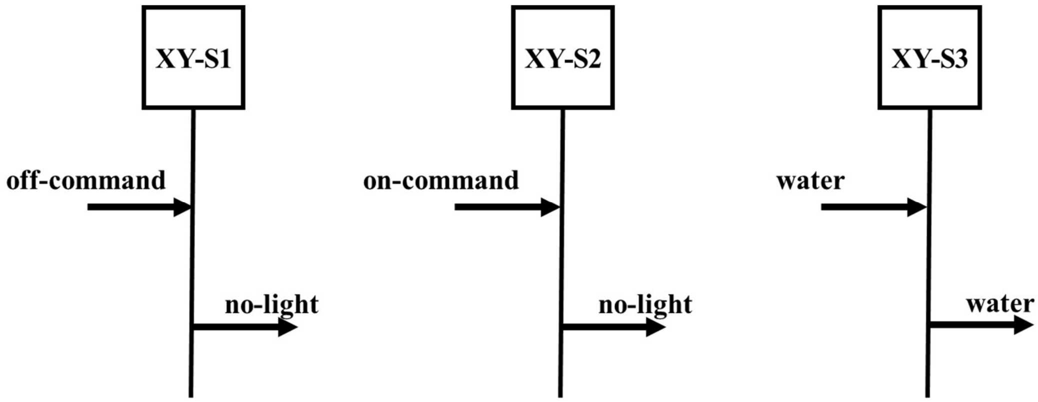

Figure 7: Sequence diagram description of the system requirements problem space of functions

3.3.2 Selection of Verification Requirement PSF

This dissertation has defined five verification requirements problem spaces VRPS, for which to correspondence to the instantiation of the PSF defined in the previous section are shown in Table 14. For interpretation of the table, VRPS1 is an instantiation of the PSF_S2.

Table 14:Mapping of subsets of verification requirement problem spaces to subsets of problem spaces of functions

VRPS	PSF
VRPS1	PSF_S2
VRPS2	PSF_S2
VRPS3	PSF_S7
VRPS4	PSF_S2
VRPS5	PSF_S2

3.3.2.1 Verification requirement problem space of functions 1

The VRPS1 has a mathematical structure consistent with PSF_S2. The remainder of this section provides Table 15 for the instantiation of IoX, Table 16 for instantiation of interfaces (F), Figure 8 for the block diagram of interface to IoX mapping, Figure 9 for the sequence diagrams (e.g., [3, 45]) of IoX transformation functions.

Table 15: Item of exchange (IoX) instantiation of a problem space of functions to form verification requirement problem space 1

IoX ID	Descriptor	Parameterization
IoX_S1	Cold	• N/A
IoX_S2	Heat	• N/A
IoX_S3	No-delicious smell	• N/A
IoX_S4	Delicious smell	• N/A

Table 16: Interface (IF) instantiation of a problem space of functions to form the verification requirement problem space 1

IF ID	Descriptor	Parameterization
IF-S1	Oven IF	N/A

IF-S2	Kitchen Air IF	N/A

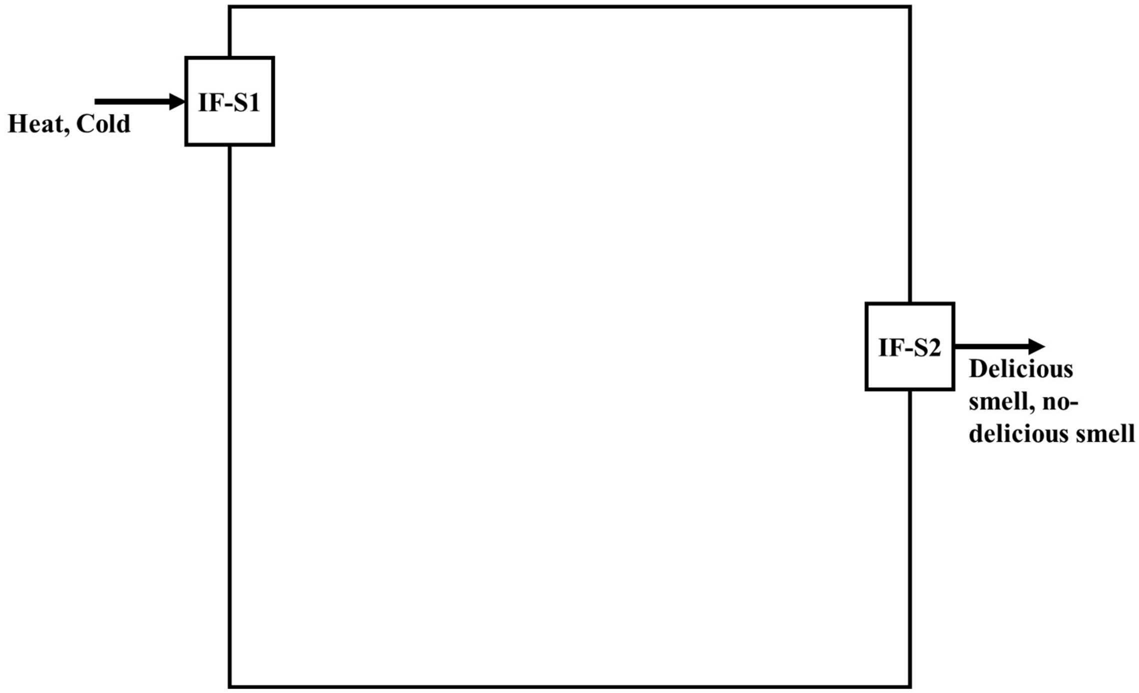

Figure 8: Block diagram description of the verification requirement problem space 1

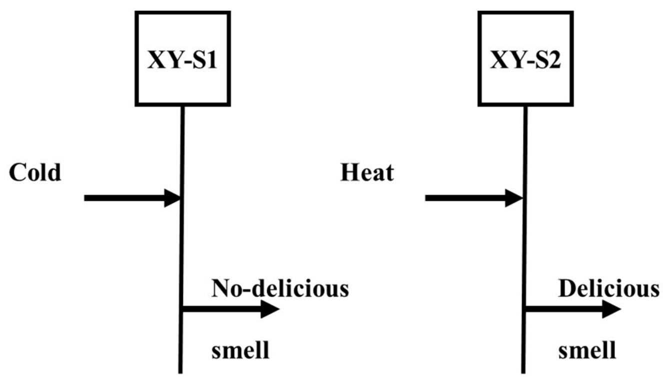

Figure 9: Sequence diagram description of the verification requirement problem space 1

3.3.2.2 Verification requirement problem space of functions 2

The VRPS2 has a mathematical structure consistent with PSF_S2. The remainder of this section provides Table 17 for the instantiation of IoX, Table 18 for instantiation of interfaces (F), Figure 10 for the block diagram of interface to IoX mapping, Figure 11 for the sequence diagrams (e.g., [3, 45]) of IoX transformation functions

Table 17: Item of exchange (IoX) instantiation of a problem space of functions to form verification requirement problem space 2

IoX ID	Descriptor	Parameterization
IoX_S1	Off-command	• N/A

IoX_S2	On-command	• N/A
IoX_S3	No-light	• Lumen: <0.5 lm
IoX_S4	Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm

Table 18: Interface (IF) instantiation of a problem space of functions to form the verification requirement problem space 2

IF ID	Descriptor	Parameterization
IF-S1	On/off IF	N/A
IF-S2	Light IF	N/A

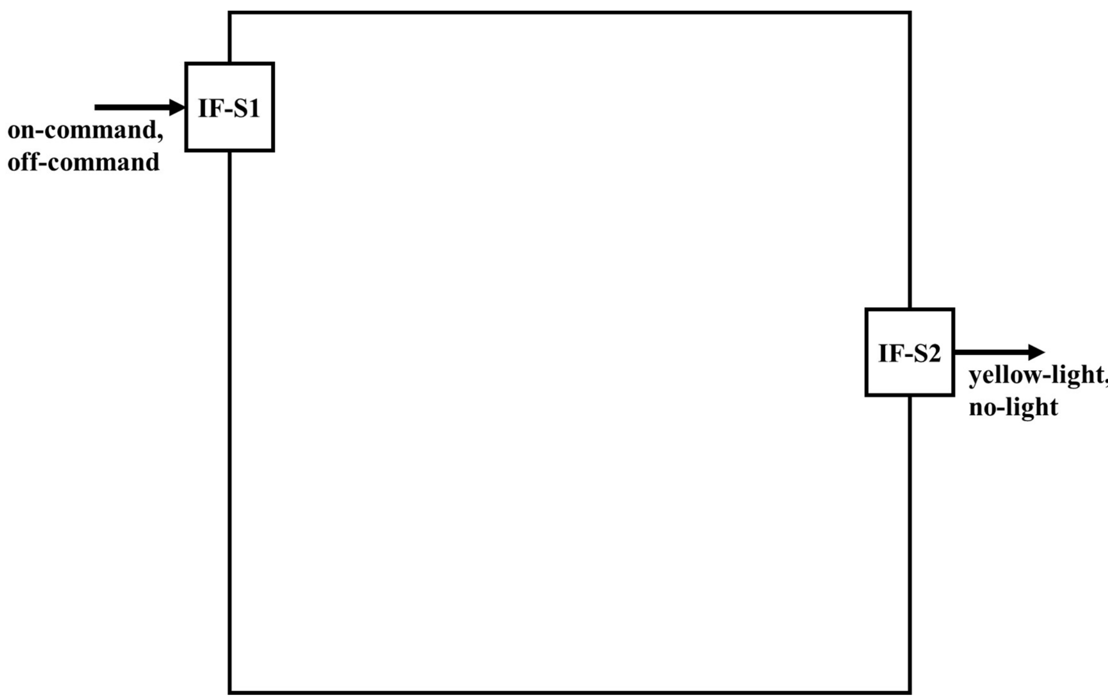

Figure 10: Block diagram description of the verification requirement problem space 2

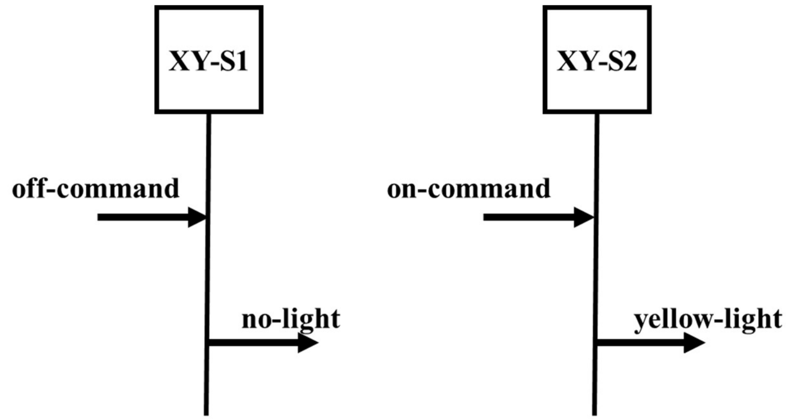

Figure 11: Sequence diagram description of the verification requirement problem space 2

3.3.2.3 Verification requirement problem space of functions 3

The VRPS3 has a mathematical structure consistent with PSF_S7. The remainder of this section provides Table 19 for the instantiation of IoX, Table 20 for instantiation of interfaces (F), Figure 12 for the block diagram of interface to IoX mapping, Figure 13 for the sequence diagrams (e.g., [3, 45]) of IoX transformation functions.

Table 19: Item of exchange (IoX) instantiation of a problem space of functions to form verification requirement problem space 3

IoX ID	Descriptor	Parameterization
IoX_S5	Water	• Pressure: 1-5 atm • Humidity: 0-100%

Table 20: Interface (IF) instantiation of a problem space of functions to form the verification requirement problem space 3

IF ID	Descriptor	Parameterization
IF-S3	Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic

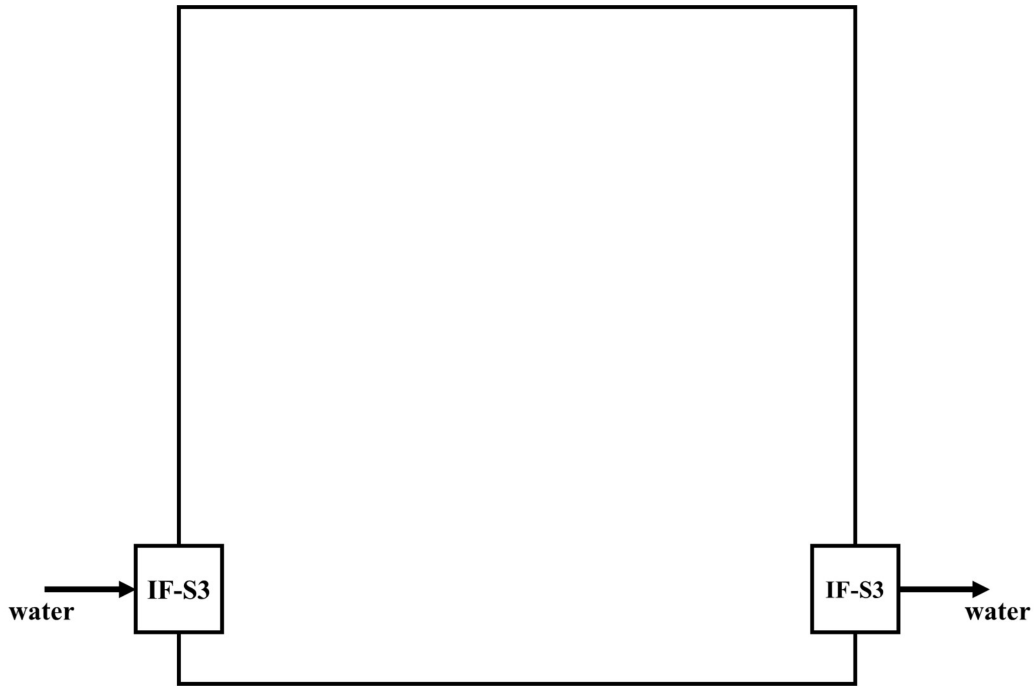

Figure 12: Block diagram description of the verification requirement problem space 3

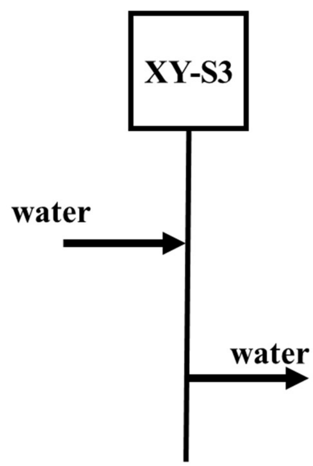

Figure 13: Sequence diagram description of the verification requirement problem space 3

3.3.2.4 Verification requirement problem space of functions 4

The VRPS4 has a mathematical structure consistent with PSF_S2. The remainder of this section provides Table 21 for the instantiation of IoX, Table 22 for instantiation of interfaces (F), Figure 14 for the block diagram of interface to IoX mapping, Figure 15 for the sequence diagrams (e.g., [3, 45]) of IoX transformation functions.

Table 21: Item of exchange (IoX) instantiation of a problem space of functions to form VRPS4

IoX ID	Descriptor	Parameterization
IoX_S1	Off-command	• N/A
IoX_S2	On-command	• N/A
IoX_S3	No-light	• Lumen: <0.5 lm

IoX_S4	Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm

Table 22: Interface (IF) instantiation of a problem space of functions to form the verification requirement problem space 4

IF ID	Descriptor	Parameterization
IF-S1	On/off IF	N/A
IF-S2	Light IF	N/A

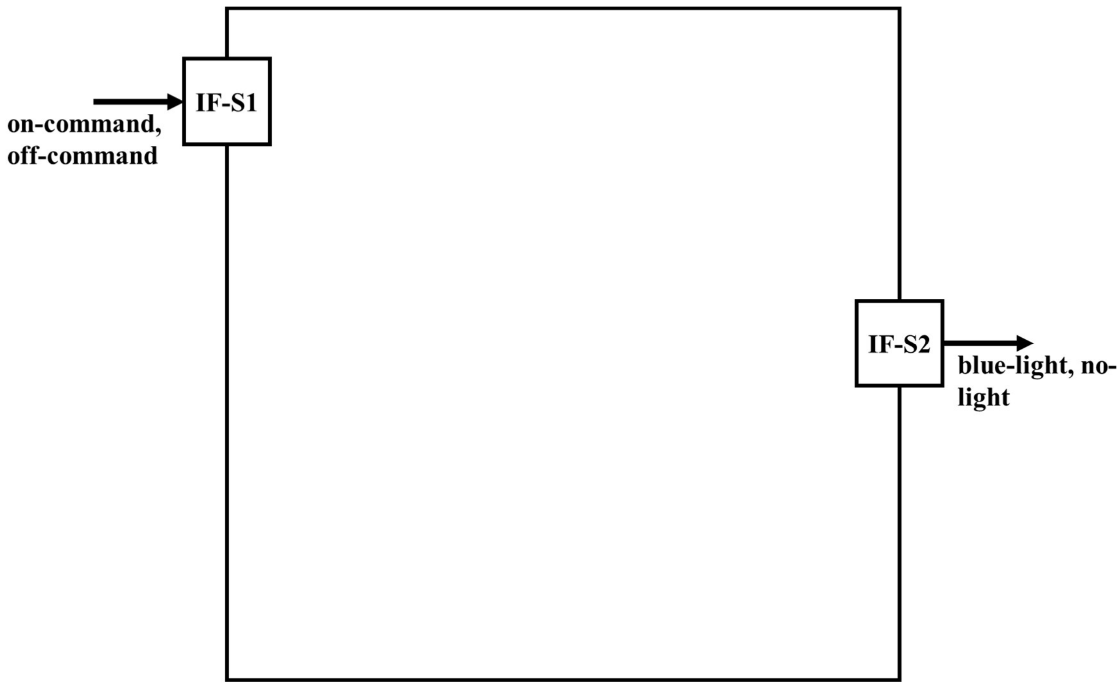

Figure 14: Block diagram description of the verification requirement problem space 4

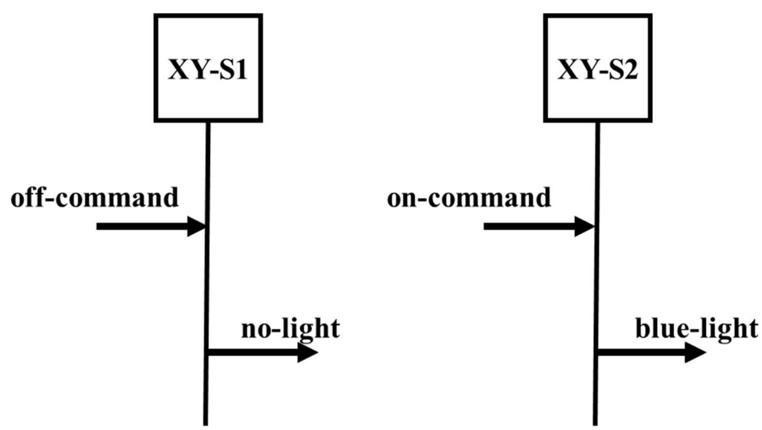

Figure 15: Sequence diagram description of the verification requirement problem space 4

3.3.2.5 Verification requirement problem space of functions 5

The VRPS5 has a mathematical structure consistent with PSF_S2. The remainder of this section provides Table 23 for the instantiation of IoX, Table 24 for instantiation of interfaces (F), Figure 16 for the block diagram of interface to IoX mapping, Figure 17 for the sequence diagrams (e.g., [3, 45]) of IoX transformation functions.

Table 23: Item of exchange (IoX) instantiation of a problem space of functions to form verification requirement problem space 5

IoX ID	Descriptor	Parameterization
IoX_S1	0	• N/A
IoX_S2	1	• N/A
IoX_S3	0	• N/A
IoX_S4	1	• N/A

Table 24: Interface (IF) instantiation of a problem space of functions to form the verification requirement problem space 5

IF ID	Descriptor	Parameterization
IF-S1	Input IF	N/A
IF-S2	Output IF	N/A

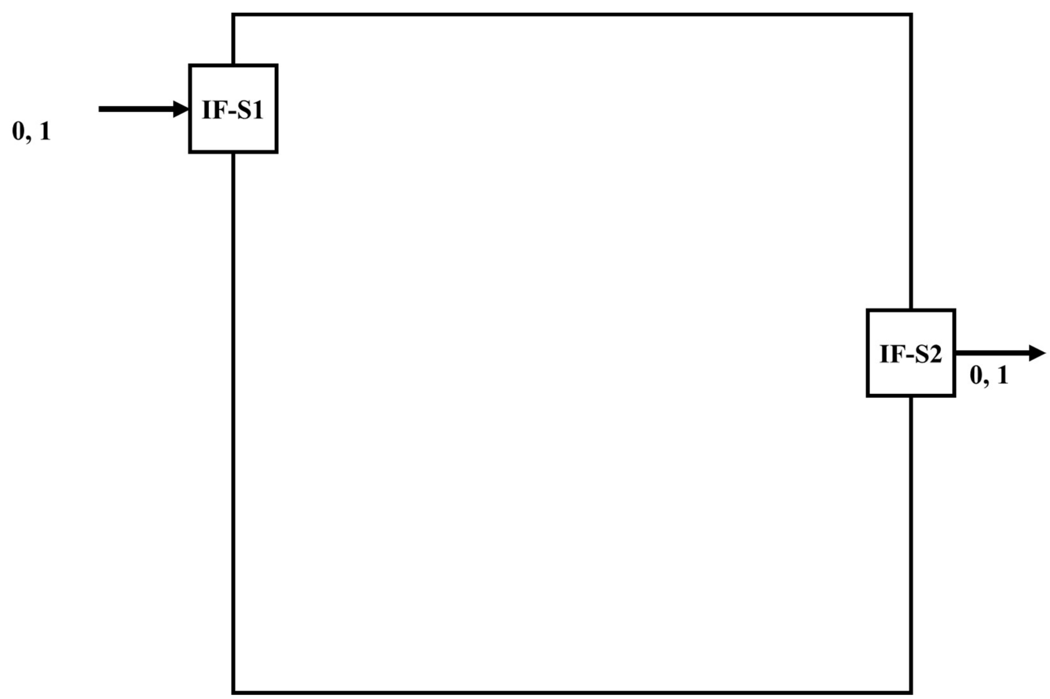

Figure 16: Block diagram description of the verification requirement problem space 5

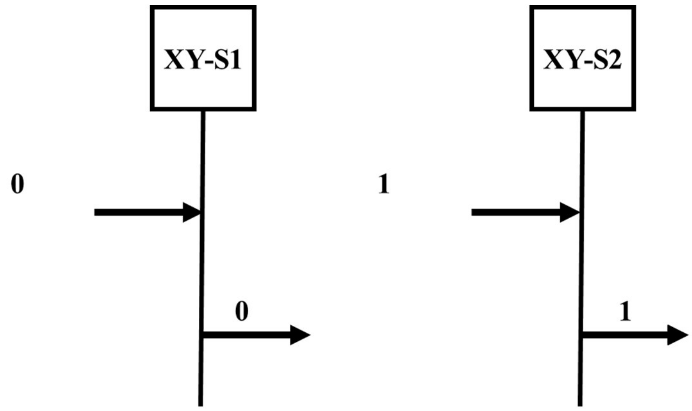

Figure 17: Sequence diagram description of the verification requirement problem space 5

3.3.3 Selection of System Designs

A total of four system designs were selected for this research. Each of the four were selected with the expectation of provable adherence to the system requirements, which means that each of the system design can be proven to be a solution within the solution space bounded by the system requirement problem space of functions. Furthermore, two of the system designs were selected at L1 system specifications and two of the system designs were selected at L2 system specifications. Additionally, the system designs were intentionally selected in pairs, with one system design being a L1 system specification and the second system design being a L2 system specification with more definition of internal structure than the L1 system specification pair. In this way, the research follows DEVS in that a L2 system can be specified on the basis of a L1 system specification; and, the research follows T3SD in that the resultant of the L2 system specification (i.e., Z@ of the buildable SD) can be homomorphically mapped to L1 system specifications (i.e., Z of the functional SD). Note, although alternative L2 systems may be specified, this is not necessary to address the research question.

Furthermore, as a reminder, this dissertation is explicitly using the term pedigree rather than fidelity. The focus of this research is on early verification in which case the end product is (or may) not be realized; and, therefore, fidelity cannot be determined or may be limited to a qualitative statement. However, pedigree may be determined through the existence of SD and quantifiable representativeness (i.e., equivalence) in the form of morphisms. Although two pairs of SD were selected and many other pairs could have been added, only a small set of SD is necessary to address the research question; which, at minimum sufficiency, would be one set of SD and the extra set only adds to the validity of the results.

The Table 25 shows selection of system models that serve as the basis for each of system design. For interpretation of the table, SD1 is an instantiation of the ZAC1.

Table 25: Mapping of system designs (SD) to system models (SM)

System Design ID	System model basis
SD1	ZAC1

SD2	ZBC1
SD3	ZAC2
SD4	ZBC2

3.3.3.1 System Design 1 (SD1)

The tables show IoX (Table 26) and IF (Table 27) instantiation of system model ZAC1 to form system design SD1.

This SD was selected to serve as a flashlight defined at L1, which has two-states, accepts on/off commands in the form of force, provides yellow-light, and is water-resistant. This SD is intended to adhere to the SR and is paired with SD3.

Table 26: Item of exchange (IoX) instantiation of a SM to form SD1

IoX ID	Descriptor	Parameterization
IoX_A1	Off-command	• Force: 0.5 N
IoX_A2	On-command	• Force: 0.5 N
IoX_A3	No-light	• Lumen: <0.5 lm
IoX_A4	Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm
IoX_C1	Water	• Pressure: 1-5 atm • Humidity: 0-100%

Table 27: Interface (IF) instantiation of a SM to form SD1

IF ID	Descriptor	Parameterization
IF-A1	On/off IF	• Diameter: 15 mm • Material: black rubber
IF-A2	Light IF	• Diameter: 57 mm • Material: clear plastic
IF-C1	Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic

3.3.3.2 System Design 2 (SD2)

The tables show the IoX (Table 28) and IF (Table 29) instantiation of system model ZBC1 to form system design SD2.

This SD was selected to serve as a flashlight defined at L1, which has three-states accepts on/off commands in the form of torque, provides yellow-light, and is water-resistant. This SD is intended to adhere to the SR and is paired with SD4.

Table 28: Item of exchange (IoX) instantiation of a SM to form SD2

IoX ID	Descriptor	Parameterization
IoX_B1	Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise
IoX_B2	On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise
IoX_B3	On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise
IoX_B4	On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise
IoX_B5	No-light	• Lumen: <0.5 lm
IoX_B6	Yellow-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm
IoX_B7	Yellow-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm
IoX_C1	Water	• Pressure: 1-6 atm • Humidity: 0-100%

Table 29: Interface (IF) instantiation of a SM to form SD2

IF ID	Descriptor	Parameterization
IF-B1	On/off IF	• Diameter: 50 mm • Material: black plastic
IF-B2	Light IF	• Diameter: 45 mm • Material: clear plastic
IF-C1	Water IF	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic

3.3.3.3 System Design 3 (SD3)

The tables show the IoX (Table 30), IF (Table 31), and component (Table 32) instantiation of system model ZAC2 to form system design SD3.

This SD was selected to serve as a flashlight defined at L2, which has components that provide the light functionality and water-resistance, resultant system model with two-states, accepts on/off commands in the form of force, provides yellow-light, and is water-resistant. This SD is intended to adhere to the SR and is paired with SD3.

Table 30: Item of exchange (IoX) instantiation of a SM to form SD3

IoX ID	Descriptor	Parameterization
IoX_A1	Off-command	• Force: 0.5 N
IoX_A2	On-command	• Force: 0.5 N
IoX_A3	No-light	• Lumen: <0.5 lm
IoX_A4	Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm
IoX_A5	No-power	• Voltage: <0.01 V
IoX_A6	Power	• Voltage: 3 V
IoX_C1	Water	• Pressure: 1-5 atm • Humidity: 0-100%

Table 31: Interface (IF) instantiation of a SM to form SD3

IF ID	Descriptor	Parameterization
IF-A1	On/off IF	• Diameter: 15 mm • Material: black rubber
IF-A2	Light IF	• Diameter: 57 mm • Material: clear plastic
IF-A3	Power IF	• Material: black plastic
IF-C1	Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic

Table 32: Mapping of SM to components of SD3

Components	Descriptor
ZAD	Light switch
ZAE	Yellow LED
ZC	Water-resistant case

3.3.3.4 System Design 4 (SD4)

The tables show the IoX (Table 33), IF (Table 34), and component (Table 35) instantiation of system model ZBC2 to form system design SD4.

Table 33: Item of exchange (IoX) instantiation of a SM to form SD4

IoX ID	Descriptor	Parameterization
IoX_B1	Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise
IoX_B2	On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise
IoX_B3	On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise
IoX_B4	On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise
IoX_B5	No-light	• Lumen: <0.5 lm
IoX_B6	Yellow-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm
IoX_B7	Yellow-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm
IoX_B8	No-power	• Voltage: <0.01V
IoX_B9	Power 1	• Voltage: 1.5V
IoX_B10	Power 2	• Voltage: 3V
IoX_C1	Water	• Pressure: 1-6 atm • Humidity: 0-100%

Table 34: Interface (IF) instantiation of a SM to form SD4

IF ID	Descriptor	Parameterization
IF-B1	On/off IF	• Diameter: 50 mm • Material: black plastic
IF-B2	Light IF	• Diameter: 45 mm • Material: clear plastic

IF-B3	Power IF	• Material: black plastic
IF-C1	Water IF	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic

Table 35: Mapping of SM to components of SD4

Components	Descriptor
ZBD	Light switch
ZBE	Yellow LED
ZC	Water-resistant case

3.3.4 Selection of Verification Models

The Table 36 shows selection of system models that serve as the basis for each of verification model. For interpretation of the table, VM1 is an instantiation of the ZAC1.

Table 36: Mapping of verification models (VM) to system models (SM) and their description

VM ID	System model basis	Descriptor
VM1	ZAC1	SD1, Flashlight, L1
VM2	ZBC1	SD2, Flashlight, L1
VM3	ZAC2, ZAD, ZAE, ZC	SD3, Flashlight, L2
VM4	ZBC2, ZBD, ZBE, ZC	SD4, Flashlight, L2
VM5	ZC	Water resistant, L1
VM6	ZA2, ZAD, ZAE	SD3-based light, L2
VM7	ZAC1	Symbolic, L1
VM8	ZA2, ZAD, ZAE	Blue light, 2-state, L2
VM9	ZB2, ZBD, ZBE	Blue light, 3-state, L2
VM10	ZB	RGB Pen, L1
VM11	ZA	Pizza, L1
VM12	ZA	Fireflies, L1
VM13	ZA	Hand-radio, L1
VM14	ZC	Pressure vessel, L1
VM15	ZC	Dry-bag, L1
VM16	ZAC1	Dry-bag + Fireflies, L1
VM17	ZAC1	Water-proof radio, L1
VM18	ZAC1	Submarine + light, L1

The selection of VM was carried out as follows: Because all SD are potential VM, the four SD also serve as the first four VM. VM5-9 were selected due to initial belief that they would be morphically equivalent to the SD. Some of the VM were selected as knowns to adhere to specific VRPS; for example, VM7 has IoX/IO as “1s” and “0s” and has a corresponding VRPS to which VM7 is known to adhere. VM10-18 were selected to intentionally have a sense of counter-intuitive nature, some of which were not known to have (or not have) morphic equivalence to SD at the onset of the research. For example, the "Pizza VM" was selected due to an initial belief that it is improbable for there to exist morphic equivalence between a pizza and a flashlight. Furthermore, VM12-18 were intentionally created to explore potential limitations in the definition of VM directly from SR as well as the assumptions related to treating SR as orthogonal subsets.

3.3.4.1 Verification Model 1 (VM1)

The verification model VM1 is SD1; therefore, we refer the reader to section 3.3.3.1 for instantiation of the corresponding system model.

3.3.4.2 Verification Model 2 (VM2)

The verification model VM1 is SD2 therefore, we refer the reader to section 3.3.3.2 for instantiation of the corresponding system model.

3.3.4.3 Verification Model 3 (VM3)

The verification model VM1 is SD3 therefore, we refer the reader to section 3.3.3.3 for instantiation of the corresponding system model.

3.3.4.4 Verification Model 4 (VM4)

The verification model VM1 is SD4; therefore, we refer the reader to section 3.3.3.4 for instantiation of the corresponding system model.

3.3.4.5 Verification Model 5 (VM5)

The tables show the IoX (Table 37) and IF (Table 38) instantiation of system model ZC to form verification model VM5.

Table 37: Item of exchange (IoX) instantiation of a SM to form VM5

IoX ID	Descriptor	Parameterization
IoX_C1	Water	• Pressure: 1-5 atm • Humidity: 0-100%

Table 38: Interface (IF) instantiation of a SM to form VM5

IF ID	Descriptor	Parameterization
IF-C1	Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic

3.3.4.6 Verification Model 6 (VM6)

The tables show the IoX (Table 39), IF (Table 40), and component (Table 41) instantiation of system model ZA2 to form verification model VM6.

Table 39: Item of exchange (IoX) instantiation of a SM to form VM6

IoX ID	Descriptor	Parameterization
IoX_A1	Off-command	• Force: 0.5 N
IoX_A2	On-command	• Force: 0.5 N
IoX_A3	No-light	• Lumen: <0.5 lm
IoX_A4	Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm
IoX_A5	No-power	• Voltage: <0.01 V
IoX_A6	Power	• Voltage: 3 V

Table 40: Interface (IF) instantiation of a SM to form VM6

IF ID	Descriptor	Parameterization
IF-A1	On/off IF	• Diameter: 15 mm • Material: black rubber
IF-A2	Light IF	• Diameter: 57 mm • Material: clear plastic
IF-A3	Power IF	• Material: black plastic

Table 41: Mapping of SM to components of VM6

Components	Descriptor
ZAD	Light switch
ZAE	Yellow LED

3.3.4.7 Verification Model 7 (VM7)

The tables show the IoX (Table 42) and IF (Table 43) instantiation of system model ZA to form verification model VM7.

Table 42: Item of exchange (IoX) instantiation of a SM to form VM7

IoX ID	Descriptor	Parameterization
IoX_A1	0	• N/A
IoX_A2	1	• N/A
IoX_A3	0	• N/A
IoX_A4	1	• N/A

Table 43: Interface (IF) instantiation of a SM to form VM7

IF ID	Descriptor	Parameterization
IF-A1	Input IF	• Diameter: 15 mm • Material: black rubber

IF-A2	Output IF	• Diameter: 57 mm • Material: clear plastic

3.3.4.8 Verification Model 8 (VM8)

The tables show the IoX (Table 44), IF (Table 45), and component (Table 46) instantiation of system model ZA2 to form verification model VM8.

Table 44: Item of exchange (IoX) instantiation of a SM to form VM8

IoX ID	Descriptor	Parameterization
IoX_A1	Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise
IoX_A2	On-command	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise
IoX_A3	No-light	• Lumen: <0.5 lm
IoX_A4	Blue-light	• Wavelength: 475 nm [blue] • Lumen: 400 lm
IoX_A5	No-power	• Voltage: <0.01 V
IoX_A6	Power	• Voltage: 5 V

Table 45: Interface (IF) instantiation of a SM to form VM8

IF ID	Descriptor	Parameterization
IF-A1	On/off IF	• Diameter: 15 mm • Material: black rubber
IF-A2	Light IF	• Diameter: 57 mm • Material: clear plastic
IF-A3	Power IF	• Material: black plastic

Table 46: Mapping of SM to components of VM8

Components	Descriptor
ZAD	Arduino + Potentiometer
ZAE	Blue LED

3.3.4.9 Verification Model 9 (VM9)

The tables show the IoX (Table 47), IF (Table 48), and component (Table 49) instantiation of system model ZB2 to form verification model VM9.

Table 47: Item of exchange (IoX) instantiation of a SM to form VM9

IoX ID	Descriptor	Parameterization
IoX_B1	Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise
IoX_B2	On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise
IoX_B3	On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise
IoX_B4	On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise
IoX_B5	No-light	• Lumen: <0.5 lm
IoX_B6	Blue-light 1	• Wavelength: 475 nm [blue] • Lumen: 200 lm
IoX_B7	Blue-light 2	• Wavelength: 475 nm [blue] • Lumen: 400 lm
IoX_B8	No-power	• Voltage: <0.01V
IoX_B9	Power 1	• Voltage: 1V
IoX_B10	Power 2	• Voltage: 2V
IoX_C1	Water	• Pressure: 1-6 atm • Humidity: 0-100%

Table 48: Interface (IF) instantiation of a SM to form VM9

IF ID	Descriptor	Parameterization
IF-B1	On/off IF	• Diameter: 50 mm • Material: black plastic
IF-B2	Light IF	• Diameter: 45 mm • Material: clear plastic

IF-B3	Power IF	• Material: black plastic
IF-C1	Water IF	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic

Table 49: Mapping of SM to components of VM9

Components	Descriptor
ZAD	Arduino + Potentiometer
ZAE	Blue LED

3.3.4.10 Verification Model 10 (VM10)

The tables show the IoX (Table 50) and IF (Table 51) instantiation of system model ZB to form verification model VM10.

Table 50: Item of exchange (IoX) instantiation of a SM to form VM10

IoX ID	Descriptor	Parameterization
IoX_B1	Green to Red	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise
IoX_B2	Red to Green	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise
IoX_B3	Green to Blue	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise
IoX_B4	Blue to Green	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise
IoX_B5	Red Ink	• Wavelength: 650 nm [red]
IoX_B6	Green Ink	• Wavelength: 510 nm [green]
IoX_B7	Blue Ink	• Wavelength: 475 nm [blue]

Table 51: Interface (IF) instantiation of a SM to form VM10

IF ID	Descriptor	Parameterization
IF-B1	Color Change IF	• Diameter: 5 mm • Material: black plastic
IF-B2	Ink IF	• Diameter: 2 mm • Material: brass

3.3.4.11 Verification Model 11 (VM11)

The tables show the IoX (Table 52) and IF (Table 53) instantiation of system model ZA to form verification model VM11.

Table 52: Item of exchange (IoX) instantiation of a SM to form VM11

IoX ID	Descriptor	Parameterization
IoX_A1	Cold	• N/A
IoX_A2	Hot	• N/A
IoX_A3	No delicious smell	• N/A
IoX_A4	Delicious smell	• N/A

Table 53: Interface (IF) instantiation of a SM to form VM11

IF ID	Descriptor	Parameterization
IF-A1	Oven IF	• N/A
IF-A2	Kitchen Air IF	• N/A

3.3.4.12 Verification Model 12 (VM12)

The tables show the IoX (Table 54) and IF (Table 55) instantiation of system model ZA to form verification model VM12.

Table 54: Item of exchange (IoX) instantiation of a SM to form VM12

IoX ID	Descriptor	Parameterization
IoX_A1	Off-trigger	• N/A
IoX_A2	On-trigger	• N/A
IoX_A3	No-light	• Lumen: <0.5 lm
IoX_A4	Firefly light	• Color: yellow • Wavelength: 590 nm • Lumen: 325 lm

Table 55: Interface (IF) instantiation of a SM to form VM12

IF ID	Descriptor	Parameterization
IF-A1	Trigger IF	• N/A
IF-A2	Light IF	• N/A

3.3.4.13 Verification Model 13 (VM13)

The tables show the IoX (Table 56) and IF (Table 57) instantiation of system model ZA to form verification model VM13.

Table 56: Item of exchange (IoX) instantiation of a SM to form VM13

IoX ID	Descriptor	Parameterization
IoX_A1	Off-command	• N/A
IoX_A2	On-command	• N/A
IoX_A3	Radio-off	• Lumen: <0.5
IoX_A4	Radio-on	• N/A

Table 57: Interface (IF) instantiation of a SM to form VM13

IF ID	Descriptor	Parameterization
IF-A1	Off IF	• N/A
IF-A2	Radio Display IF	• N/A

3.3.4.14 Verification Model 14 (VM14)

The tables show the IoX (Table 58) and IF (Table 59) instantiation of system model ZC to form verification model VM14.

Table 58: Item of exchange (IoX) instantiation of a SM to form VM14

IoX ID	Descriptor	Parameterization
IoX_C1	Water	• Pressure: -5-1000 atm • Humidity: 0-100%

Table 59: Interface (IF) instantiation of a SM to form VM14

IF ID	Descriptor	Parameterization
IF-C1	Water IF	• N/A

3.3.4.15 Verification Model 15 (VM15)

The tables show the IoX (Table 60) and IF (Table 61) instantiation of system model ZC to form verification model VM15.

Table 60: Item of exchange (IoX) instantiation of a SM to form VM15

IoX ID	Descriptor	Parameterization
IoX_C1	Water	• Pressure: 1-5 atm • Humidity: 0-100%

Table 61: Interface (IF) instantiation of a SM to form VM15

IF ID	Descriptor	Parameterization
IF-C1	Water IF	• N/A

3.3.4.16 Verification Model 16 (VM16)

The tables show the IoX (Table 62) and IF (Table 63) instantiation of system model ZAC1 to form verification model VM16.

Table 62: Item of exchange (IoX) instantiation of a SM to form VM16

IoX ID	Descriptor	Parameterization
IoX_A1	Off-trigger	• N/A
IoX_A2	On-trigger	• Lumen: <0.5
IoX_A3	No-light	• N/A
IoX_A4	Firefly light	• Color: yellow • Wavelength: 590 nm • Lumen: 325 lm
IoX_C1	Water	• Pressure: 1-5 atm • Humidity: 0-100%

Table 63: Interface (IF) instantiation of a SM to form VM16

IF ID	Descriptor	Parameterization
IF-G1	Trigger IF	• N/A
IF-G2	Light IF	• N/A
IF-C1	Water IF	• N/A

3.3.4.17 Verification Model 17 (VM17)

The tables show the IoX (Table 64) and IF (Table 65) instantiation of system model ZAC1 to form verification model VM17.

Table 64: Item of exchange (IoX) instantiation of a SM to form VM17

IoX ID	Descriptor	Parameterization
IoX_A1	Off-command	• N/A
IoX_A2	On-command	• N/A
IoX_A3	Radio-off	• Lumen: <0.5
IoX_A4	Radio-on	• N/A
IoX_C1	Water	• Pressure: 1-5 atm • Humidity: 0-100%

Table 65: Interface (IF) instantiation of a SM to form VM17

IF ID	Descriptor	Parameterization

IF-A1	Off IF	• N/A
IF-A2	Radio Display IF	• N/A
IF-C1	Water IF	• N/A

3.3.4.18 Verification Model 18 (VM18)

The tables show the IoX (Table 66) and IF (Table 67) instantiation of system model ZAC1 to form verification model VM18.

Table 66: Item of exchange (IoX) instantiation of a SM to form VM18

IoX ID	Descriptor	Parameterization
IoX_A1	Off-command	• N/A
IoX_A2	On-command	• N/A
IoX_A3	No-light	• Lumen: <0.5 lm
IoX_A4	Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 1000 lm
IoX_C1	Water	• Pressure: -5-1,000 atm • Humidity: 0-100%

Table 67: Interface (IF) instantiation of a SM to form VM18

IF ID	Descriptor	Parameterization
IF-A1	On/off IF	• N/A
IF-A2	Light IF	• N/A
IF-C1	Water IF	• N/A

3.4 Proof of tabular relationships

3.4.1 Proof of morphisms between PSF

Because all the PSF are subsets of superset, it is not necessary to prove morphic equivalence from the PSF subsets to the superset. And, this dissertation only considers morphism from subsets of PSF to the superset. Therefore, no further proof is necessary.

Given that T3SD does not have a morphism between PSF, it cannot be used as the basis for this morphism. However, DEVS has a morphism between IO functions (IOFO morphism chapter 15.3 [73]), which serves as the basis for the morphisms of PSF for this dissertation.

Note, use of the IOFO morphism from DEVS requires an assumption because IOFO is not strictly a problem space. This methodological decision is not expected to change the results of this dissertation. Exploration of problem space morphism in the field of topology is left for future research.

Furthermore, the use of the DEVS-based morphism is substantiated through software means, which is discussed further in the validation section.

3.4.2 Proof of adherence of SM to PSF

Proof of adherence of SM to PSF is provided in tabular form through mapping IoX, mapping IF, mapping IF to IoX function (F), and mapping XY (IoX function) of the PSF to the state transitions (N) and the output of the final state in the trajectory (R) of the SM.

Furthermore, the use of the DEVS-based SM and PSF relationship is substantiated through software means, which is discussed further in the validation section.

A visual summary of the process used is provided in Figure 18.

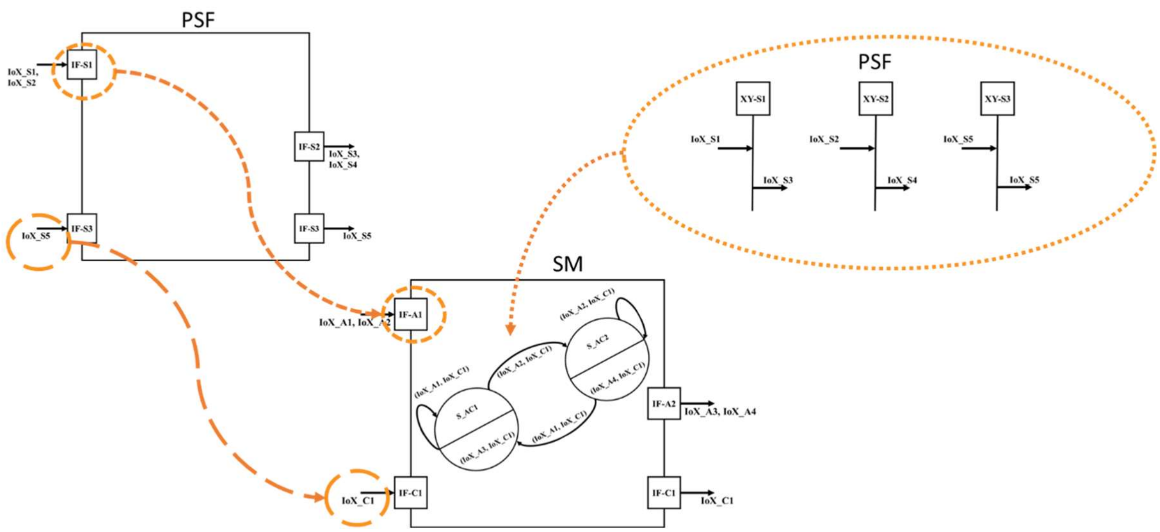

Figure 18: Visual description of proof of system model adherence to a problem space of functions

The results are summarized in a table at the beginning of the associated section(s) and supporting results are provided in the Appendix (7.6).

3.4.3 Proof of morphisms between SM

As discussed previously the SM are based on both T3SD and DEVS. In T3SD there exists only a morphism between SM at L1. In DEVS morphisms exist at multiple levels; however, the L2 system specification of SM is based on T3SD. Therefore, the L1 morphism between SM is based on T3SD morphism as well as the IO System morphism (chapter 15.4 [73]); and, the L2 morphism between SM is based on the coupling morphisms (e.g., chapter 15.7 and 15.8 [73]).

Proof is provided in tabular form through mapping IoX, IF, states, state transitions (N), and the output of the final state in the trajectory (R) between the SM.

Furthermore, the use of the DEVS-based morphisms is substantiated through software means, which is discussed further in the validation section.

A visual description of L1 morphism is shown in Figure 19.

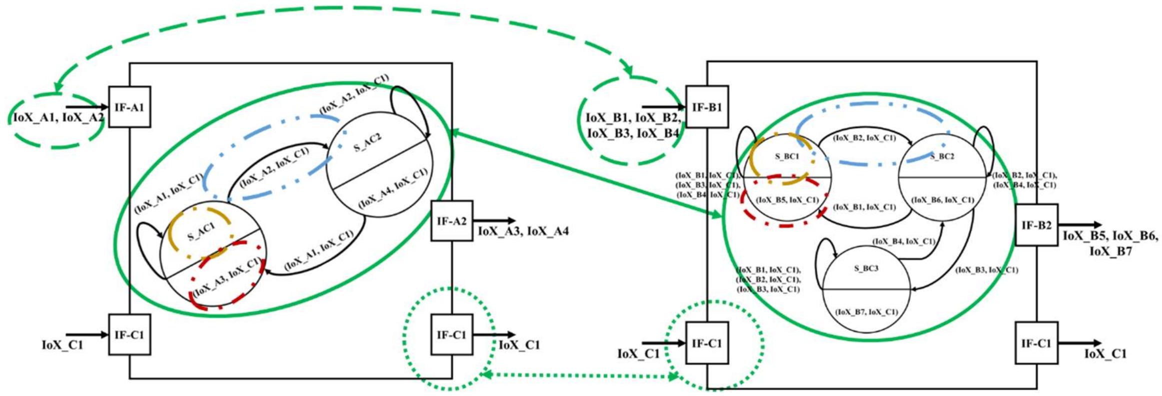

Figure 19: Visual description of a level 1 (L1) morphism between L1 system model specifications

A visual description of L2 morphism and resultant L1 morphism is shown in Figure 20.

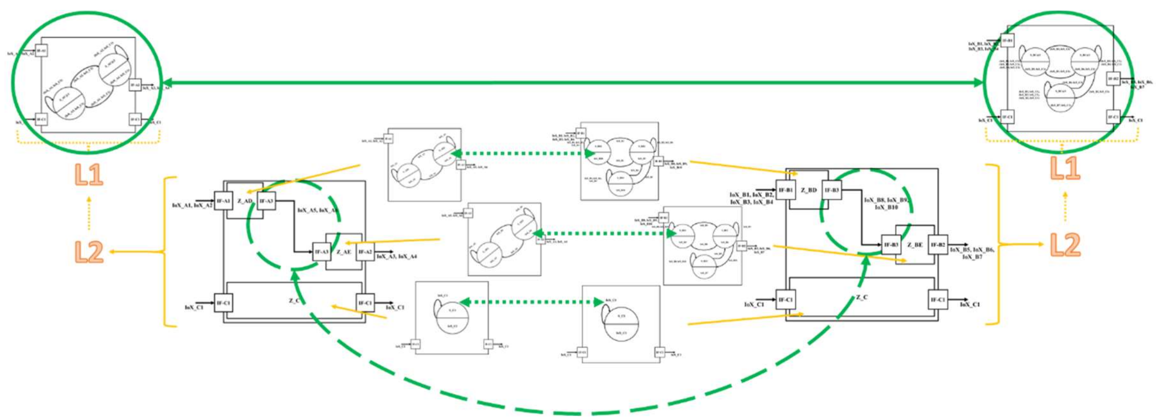

Figure 20: Visual description of a level 2 (L2) morphism between L2 system model specifications and level 1 (L1) morphism between resultant L1 system model specifications

The results are summarized in a table at the beginning of the associate section(s) and supporting results are provided in the Appendix (7.7).

3.4.4 Proof of morphisms between SR and VRPS

Recall, the SR and VRPS are instantiations of the PSF. Therefore, much of the morphic proof is provided through proof of morphism between PSF. However, the morphic proof here is between instantiations of PSF in tabular form mapping IoX, mapping IF, and mapping IF to IoX function (F) of the SR and VRPS.

The results are summarized in a table at the beginning of the associated section(s) and supporting results are provided in the Appendix (7.8).

3.4.5 Proof of morphisms between SD and VM

Recall, the SD and VM are instantiations of the SM. Therefore, much of the morphic proof is provided through proof of morphism between SM. However, the morphic proof here is between instantiations of SD and VM in tabular form, mapping IoX and IF.

The results are summarized in a table at the beginning of the section and supporting results are provided in the Appendix (7.12).

3.4.6 Verification model morphic conditions (VMMC)

For this dissertation, verification model morphic conditions (VMMC) are the conditions that describe the expected degree of morphic equivalence (i.e., pedigree) between verification models and system designs.

For this dissertation, the VMMC are framed within the context of the PSF subsets and within the context of a level of system specification (L1 and L2). For example, a VMMC may require an identity isomorphism at L1 with respect to PSF_S1; in which case the VM is required to have a one-to-one mapping between IoX, IoX instantiation, interfaces, interface instantiation, states, and transitions with respect to PSF_S1 and functions XY-S1, XY-S2, XY-S3.

The results from the proof of morphic equivalence between the VM and SD are used as a basis for determining which VM are included (i.e., adhere to VMMC) versus excluded (i.e., do not adhere to VMMC).

A total of six VMMC were used for this dissertation, which are defined in Table 68 below:

Table 68: Description of verification model morphic conditions (VMMC) for desired pedigree

VMMC#	Description
VMMC1	Isomorphism at L1 with respect to PSF_S1
VMMC2	Identity isomorphism at L2 with respect to PSF_S1
VMMC3	Parameter homomorphism at L2 with respect to PSF_S2, PSF_S3, and PSF_S4
VMMC4	Homomorphism at L1 with respect to PSF_S7
VMMC5	Isomorphism at L1 with respect to PSF_S7
VMMC6	Homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4

Note, each VMMC was selected at random without prior knowledge of which VM would adhere to the VMMC.

The results are summarized in a table at the beginning of the section.

3.4.7 Defined VM through combined VRPS, VMMC, and SD knowledge

For this part of the dissertation, the acceptably defined VM are the intersect of VM that adhere to VRPS, VM that are morphically equivalent to SD, and VM that adhere to the VMMC. Each combination is characterized in tabular form, leveraging previous results.

3.5 Characterization of resultant metamodel of verification artifacts

The previous research tasks provide the foundations for characterization of a resultant metamodel of verification artifacts. The metamodel is defined graphically showing the verification artifacts and their various relationships. Furthermore, a taxonomy is provided for textual definitions of the verification artifacts and their various relationships.

3.6 Validation of results

3.6.1 Software validation SM and PSF

Each SM was modeled in the MS4 Me software [76], which ensures that each SM is modeled in accordance with DEVS mathematical structures.

A difference in the tabular SM and the DEVS software-based SM is the use of the time advanced function of DEVS. Note, DEVS is commonly referred to as computational systems theory because it was created with the intent of performing computations through systems theoretic structures. An alternative name for DEVS is the Theory of Modeling and Simulation, with the computational emphasis being on simulation and as such DEVS includes the time advanced function to enable time-based simulation. DEVS was based on Wymore's Mathematical Theory of SE [22] as well as its General Systems Theory (GEST) implementor [77]; and, furthermore, both DEVS and T3SD are based on the Moore-state machine. The above suggests that the tabular SM and the DEVS software-based SM should be considered as equivalent.

A special case of note in distinction between DEVS and T3SD was discovered during the conduct of this research resulting from the coupling of component SM. Some tabular SM are defined such that simultaneous IoX are received as inputs and simultaneous IoX are produced as output from SM. For the tabular SM, this simultaneity of IoX is consistent between SM specified at L1 and corresponding SM specified at L2. On initial creation of the DEVS-software implementation of the corresponding SM, the simultaneous IoX were observed for the SM specified at L1 and, however, the simultaneous IoX were not observed for the outputs of the SM specified at L2. As discussed in the previous paragraph, a feature of DEVS is the time advance function, which is expressly necessary for time-based simulation. The lack of simultaneity was discovered to be a misalignment in the time-advanced functions for the coupled components. Specifically, because there are two components coupled in series with one orthogonal component in parallel, the single orthogonal component produced an output with zero delay; whereas, the components coupled in series required a further step in the simulation. This special case was addressed by adding a time delay to the backend component of the parallel coupling as well as to the single orthogonal component. A lesson here is that (1) all real systems experience time delay between IO, (2) T3SD does not appear to strictly account for this time delay, and (3) DEVS is created for the purpose of modeling real systems and, therefore, does account for timing.

The SM and PSF are considered here together because the DEVS-based form of PSF is necessary to validate the SM. In DEVS, there exist the notion of an experimental frame, which is consistent with functions of the PSF. An experimental frame generates inputs to the SM and accepts the outputs from the SM. Thus, the expected transformations of the PSF are validated while validating the SM.

Samples of the MS4 Me code for the SM and PSF can be found in the Appendix (7.3).

3.6.2 Software validation of SM morphisms

The DEVS software MS4 Me [76] is also used to validate the SM morphisms. The DEVS software-based SM were morphically compared through defining a state mapping between SM and IoX input trajectories. After each IoX input, the state of each SM is compared based on the state mapping. If the SM are in the same state, in accordance with the mapping, then the code returns "Equal true." If the SM are not the same state, in accordance with the mapping, then the code returns "Equal false."

As part of the validation some trajectories were selected to intentionally produce a response of "Equal false," meaning that the SM were not in the same state. This does not mean that the two SM are not homomorphic; rather, it confirms that the two defined trajectories caused misalignment in the current state. This a desired function of the morphic proof and furthers the validation through intentional 'error' injection.

Samples of the MS4 Me code for the SM and PSF can be found in the Appendix (7.3).

3.6.3 Expert review of tabular work

A subject matter expert on SE and Wymorian systems theory was selected for review of the tabular work. The expert reviewed the tabular mathematical structures, instantiations of the mathematical models, tabular proof, and expression of the resultant metamodel.

3.6.4 Expert review of software-based work

A subject matter expert on Wymorian systems theory and creator of DEVS and MS4 Me was selected for review of all software-base work to validate the tabular work. The expert reviewed the simulation SM, simulation experimental frames (i.e., PSF), and morphic proof.

3.6.5 Comparison of metamodel to state of SE practice

An output from this dissertation is a metamodel of the systems theoretic relationships between verification artifacts. The final section of the results chapter of this dissertation will define the metamodel and compare the metamodel to the following sources that document verification practices to prove contribution to advancement of SE:

1. SyML as characterized in [3, 45]
2. SE subject matter expertise as characterized in [42]

The intent here is to provide a representative sampling of the current state of practice of SE for comparison to the metamodel formed from this dissertation research. First, because SysML is known to be the leading MBSE language, SysML is believed to be representative of the state of practice of SE. Furthermore, the Practical Guide to SysML [3] and SysML Distilled [45] are known to be widely referenced sources both for citing reference to SysML and for usage in instruction on SysML. Second, the Applied Space Systems Engineering [42] book is written by a diverse set of government, industry, and academic SE subject matter experts and is believed to provide a representative sample of the state of practice of SE; therefore, the book was selected as a source for comparison.

Holistic comparison of the metamodel, defined as an outcome of this dissertation research, to all MBSE languages and reference texts is considered to be out-of-scope for this dissertation.

The following (Table 69) provides definitions used to assess the metamodel, SysML, and book in regard to relationship-based definition of verification models:

Table 69: Description of categorization of assessment used to compare models of verification artifacts between this dissertation and the state of practice

Term	Definition or Explanation
Direct	Stemming immediately from a source
Indirect	Stemming roundabout from a source
Implicit	Present but not consciously held or recognized
Explicit	Fully revealed or expressed without vagueness, implication, or ambiguity
Qualitative, descriptive	Not intended to be computational in nature
Quantitative, analytical	Intended to be computational in nature
Not applicable (N/A)	There is not intended to be a relationship between the VM fidelity/pedigree and itself
Minimally observed (M/O)	Minimal to no evidence available

4 Results

The results section is as follows:

1. Tabular proof is provided and summarized for SM definition from PSF
2. Tabular proof is provided and summarized for morphisms between SM
3. Tabular proof is provided for parameter mapping between SR and VRPS
4. Tabular proof is provided for SD adherence to SR
5. Tabular proof is provided for VM adherence to selected SR subset
6. Tabular proof is provided for VM adherence to VRPS
7. Tabular proof is provided for parameter mapping between SD and VM
8. Tabular proof is provided for adherence of VM to VMMC
9. Tabular results are provided for VM defined from a combination of SD, VRPS, and VMMC
10. Resultant metamodel is provided and compared to the state of SE practice

Within each section, a state is provided, where applicable, confirming the conduct and results of the software validation.

4.1 SM define from PSF

Table 70 provides a summary of the definition of SM from PSF. Note: ZAD, ZAE, ZBD, and ZBE are not included in this table because they are components of the SM specified at L2. A "Yes" means that the SM may be defined from the PSF. A dashed-line (-) means that the SM may not be defined from the PSF. The results were validated through the DEVS simulations in MS4 Me. The supporting results are captured in the Appendix (7.6).

Table 70: Summary results of definition of system models (SM) from problem spaces of functions (PSF)

SM ID	Defined from Problem Space of Functions						
	PSF_S1 XY-S1 XY-S2 XY-S3	PSF_S2 XY-S1 XY-S2	PSF_S3 XY-S1	PSF_S4 XY-S2	PSF_S5 XY-S1 XY-S3	PSF_S6 XY-S2 XY-S3	PSF_S7 XY-S3
ZA	-	Yes	Yes	Yes	-	-	-
ZB	-	Yes	Yes	Yes	-	-	-
ZC	-	-	-	-	-	-	Yes
ZA2	-	Yes	Yes	Yes	-	-	-
ZB2	-	Yes	Yes	Yes	-	-	-
ZAC1	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ZAC2	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ZBC1	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ZBC2	Yes	Yes	Yes	Yes	Yes	Yes	Yes

4.2 SM defined from SM

Each section below provides a table at the beginning that summarizes that morphic equivalence between SM in accordance with a level (L1 or L2) and morphism type (homomorphism or isomorphism). Each subsection provides the detail behind the summary table that includes a table that provides IoX mapping, a table that provides IF mapping, a table that provides IoX-IF mapping, and a table that provides mapping between next state (N) and final readout (R) functions of the SM. All supporting results are captured in the appendix.

4.2.1 Component morphisms

Table 71 provides the summary of definition of components from components. Each component is isomorphic to itself and, therefore, does not need to be proven and is not shown below. The results were validated through the DEVS simulations in MS4 Me. The supporting results are captured in the Appendix (7.7).

Table 71: Summary results of definition of component system models (SM) from component SM

SM ID	Defined with respect to PSF and described as [L1 and/or L2] [homomorphism (hom) or isomorphism (iso)]						
	PSF_S1 XY-S1 XY-S2 XY-S3	PSF_S2 XY-S1 XY-S2	PSF_S3 XY-S1	PSF_S4 XY-S2	PSF_S5 XY-S1 XY-S3	PSF_S6 XY-S2 XY-S3	PSF_S7 XY-S3
Components (ZAD, ZBD, ZAE, ZBE)							
ZAD-ZAD	-	L1 iso	L1 iso	L1 iso	-	-	-
ZAD-ZBD	-	L1 hom	L1 hom	L1 hom	-	-	-
ZBD-ZBD	-	L1 iso	L1 iso	L1 iso	-	-	-
ZAE-ZAE	-	L1 iso	L1 iso	L1 iso	-	-	-
ZAE-ZBE	-	L1 hom	L1 hom	L1 hom	-	-	-
ZBE-ZBE	-	L1 iso	L1 iso	L1 iso	-	-	-

4.2.2 ZAC1-based morphisms

Table 72 provides the summary of definition of SM. Each SM is isomorphic to itself and, therefore, does not need to be proven and is not shown below. The results were validated through the DEVS simulations in MS4 Me. The supporting results are captured in the Appendix (7.7).

Table 72: Summary results of definition of system models (SM) from ZAC1

SM ID	Defined with respect to PSF and described as [L1 and/or L2] [homomorphism (hom) or isomorphism (iso)]						
	PSF_S1 XY-S1 XY-S2 XY-S3	PSF_S2 XY-S1 XY-S2	PSF_S3 XY-S1	PSF_S4 XY-S2	PSF_S5 XY-S1 XY-S3	PSF_S6 XY-S2 XY-S3	PSF_S7 XY-S3
ZAC1							
ZA	-	L1 hom	L1 hom	L1 hom	-	-	-
ZB	-	L1 hom	L1 hom	L1 hom	-	-	-

ZC	-	-	-	-	-	-	L1 hom
ZA2	-	L1 hom	L1 hom	L1 hom	-	-	-
ZB2	-	L1 hom	L1 hom	L1 hom	-	-	-
ZAC1	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso
ZAC2	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso
ZBC1	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom
ZBC2	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom

4.2.3 ZAC2-based morphisms

Table 72 provides the summary of definition of SM. Each SM is isomorphic to itself and, therefore, does not need to be proven and is not shown below. Note, results from the previous section(s) were used as proof rather than repeating the process. For example, ZAC1 and ZAC2 results proven in the previous section and are not repeated here. The results were validated through the DEVS simulations in MS4 Me. The supporting results are captured in the Appendix (7.7).

Table 73: Summary results of definition of system models (SM) from ZAC2

SM ID	Defined with respect to PSF and described as [L1 and/or L2] [homomorphism (hom) or isomorphism (iso)]						
	PSF_S1 XY-S1 XY-S2 XY-S3	PSF_S2 XY-S1 XY-S2	PSF_S3 XY-S1	PSF_S4 XY-S2	PSF_S5 XY-S1 XY-S3	PSF_S6 XY-S2 XY-S3	PSF_S7 XY-S3
ZAC2							
ZA	-	L1 hom	L1 hom	L1 hom	-	-	-
ZB	-	L1 hom	L1 hom	L1 hom	-	-	-
ZC	-	-	-	-	-	-	L1 hom
ZA2	-	L2 hom	L2 hom	L2 hom	-	-	-
ZB2	-	L2 hom	L2 hom	L2 hom	-	-	-
ZAC1	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso
ZAC2	L2 iso	L2 iso	L2 iso	L2 iso	L2 iso	L2 iso	L2 iso
ZBC1	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom
ZBC2	L2 hom	L2 hom	L2 hom	L2 hom	L2 hom	L2 hom	L2 hom

4.2.4 ZBC1-based morphisms

Table 74 provides the summary of definition of SM. Each SM is isomorphic to itself and, therefore, does not need to be proven and is not shown below. Note, results from the previous section(s) were used as proof rather than repeating the process. For example, ZAC1 and ZAC2 results proven in the previous section and are not repeated here. The results were validated through the DEVS simulations in MS4 Me. The supporting results are captured in the Appendix (7.7).

Table 74: Summary results of definition of system models (SM) from ZBC1

SM ID	Defined with respect to PSF and described as [L1 and/or L2] [homomorphism (hom) or isomorphism (iso)]						
	PSF_S1 XY-S1 XY-S2 XY-S3	PSF_S2 XY-S1 XY-S2	PSF_S3 XY-S1	PSF_S4 XY-S2	PSF_S5 XY-S1 XY-S3	PSF_S6 XY-S2 XY-S3	PSF_S7 XY-S3
ZBC1							
ZA	-	L1 hom	L1 hom	L1 hom	-	-	-
ZB	-	L1 hom	L1 hom	L1 hom	-	-	-
ZC	-	-	-	-	-	-	L1 hom
ZA2	-	L1 hom	L1 hom	L1 hom	-	-	-
ZB2	-	L1 hom	L1 hom	L1 hom	-	-	-
ZAC1	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom
ZAC2	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom
ZBC1	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso
ZBC2	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso

4.2.5 ZBC2-based morphisms

Table 75 provides the summary of definition of SM. Each SM is isomorphic to itself and, therefore, does not need to be proven and is not shown below. Note, results from the previous section(s) were used as proof rather than repeating the process. For example, ZAC1 and ZAC2 results proven in the previous section and are not repeated here. The results were validated through the DEVS simulations in MS4 Me. The supporting results are captured in the Appendix (7.7).

Table 75: Summary results of definition of system models (SM) from ZBC2

SM ID	Defined with respect to PSF and described as [L1 and/or L2] [homomorphism (hom) or isomorphism (iso)]						
	PSF_S1 XY-S1 XY-S2 XY-S3	PSF_S2 XY-S1 XY-S2	PSF_S3 XY-S1	PSF_S4 XY-S2	PSF_S5 XY-S1 XY-S3	PSF_S6 XY-S2 XY-S3	PSF_S7 XY-S3
ZBC2							
ZA	-	L1 hom	L1 hom	L1 hom	-	-	-
ZB	-	L1 hom	L1 hom	L1 hom	-	-	-
ZC	-	-	-	-	-	-	L1 hom
ZA2	-	L1 hom	L1 hom	L1 hom	-	-	-
ZB2	-	L1 hom	L1 hom	L1 hom	-	-	-
ZAC1	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom	L1 hom
ZAC2	L2 hom	L2 hom	L2 hom	L2 hom	L2 hom	L2 hom	L2 hom
ZBC1	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso	L1 iso
ZBC2	L2 iso	L2 iso	L2 iso	L2 iso	L2 iso	L2 iso	L2 iso

4.3 VRPS defined from SR

In this section, the VRPS are proven to be defined from the SR. Because the VRPS have equality in underlying structures of subsets of SR, each VRPS has an initial underlying isomorphism to the SR subset through the common PSF. This section accesses the existence and type of parameter morphism and overarching subsequent morphism that exists between the VRPS and the SR subset. Because all VRPS were selected from subsets of the superset of PSF to which the SR are also based, there is no need to show a summary of the results. However, the supporting results are captured in the Appendix (7.8) in tabular form.

4.4 SD adherence to SR

This section provides proof of the SD adherence to SR based on instantiation of SM and PSF as well as prior proof of SM adherence to PSF. Because all SD were selected with explicit intent of adherence to the SR, there is no need to show a summary of the results. However, the supporting results are captured in the Appendix (7.9) in tabular form.

4.5 VM defined from SR subsets

This section provides proof of the VM adherence to SR subsets based on instantiation of SM and PSF as well as prior proof of SM adherence to PSF. Table 76 provides a summary of the results from this section. Each subsection provides the parameter mapping between the VM and SR to support the results. The supporting results are captured in the Appendix (7.10).

Table 76: Summary results of definition of verification models (VM) from system requirement (SR) problem spaces

VM#	Defined from SR functions and parameterization?					
	PSF_S1 SR superset	PSF_S3 XY-S1 SR1, SR3 + Parameter	PSF_S4 XY-S2 SR2, SR4 + Parameter	PSF_S5 XY-S1, XY-S3 SR1, SR3, SR5 + Parameter	PSF_S6 XY-S2, XY-S3 SR2, SR4, SR5 + Parameter	PSF_S7 XY-S3 SR5 + Parameter
VM1	Yes	Yes	Yes	Yes	Yes	Yes
VM2	Yes	Yes	Yes	Yes	Yes	Yes
VM3	Yes	Yes	Yes	Yes	Yes	Yes
VM4	Yes	Yes	Yes	Yes	Yes	Yes
VM5	-	-	-	-	-	Yes
VM6	-	Yes	Yes	-	-	-
VM7	-	-	-	-	-	-
VM8	-	-	-	-	-	-
VM9	-	-	-	-	-	-
VM10	-	-	-	-	-	-
VM11	-	-	-	-	-	-
VM12	-	-	-	-	-	-

VM13	-	-	-	-	-	-
VM14	-	-	-	-	-	Yes
VM15	-	-	-	-	-	Yes
VM16	-	-	-	-	-	Yes
VM17	-	-	-	-	-	Yes
VM18	Yes	Yes	Yes	Yes	Yes	Yes

4.6 VM defined from VRPS

This section provides proof of the VM adherence to VRPS sets based on instantiation of SM and PSF as well as prior proof of SM adherence to PSF. Table 77 provides a summary of the results from this section. Each subsection provides the parameter mapping between the VM and VRPS to support the results. The supporting results are captured in the Appendix (7.11).

Table 77: Summary results of definition of verification models (VM) from system requirement problem spaces (VRPS)

VM#	Defined from VRPS				
	VRPS1, PSF2 + Parameter (pizza)	VRPS2, PSF2 + Parameter (y-light)	VRPS3, PSF7 + Parameter (water)	VRPS4, PSF2 + Parameter (b-light)	VRPS5, PSF2 + Parameter (0/1)
VM1	-	Yes	Yes	-	-
VM2	-	Yes	Yes	-	-
VM3	-	Yes	Yes	-	-
VM4	-	Yes	Yes	-	-
VM5	-	-	Yes	-	-
VM6	-	Yes	-	-	-
VM7	-	-	-	-	Yes
VM8	-	-	-	Yes	-
VM9	-	-	-	Yes	-
VM10	-	-	-	-	-
VM11	Yes	-	-	-	-
VM12	-	-	-	-	-
VM13	-	-	-	-	-
VM14	-	-	-	-	-
VM15	-	-	-	-	-
VM16	-	-	-	-	-
VM17	-	-	-	-	-
VM18	-	Yes	-	-	-

4.7 VM defined from SD

This section provides proof of the VM definition from SD based on instantiation of SM as well as prior proof of SM definition from SM. Tables at the beginning of each subset provide a summary of the results from this section. Each subsection provides the parameter mapping between the VM and SD to support the results. The supporting results are captured in the Appendix (7.12).

4.7.1 VM defined from SD1

Table 78 provides a summary of the results, which are substantiation by the supporting results captured in the Appendix (7.12).

Table 78: Summary results of definition of verification models (VM) from SD1

VM#	Defined with respect to SD and described as [L1 and/or L2] [parameter] and/or [homomorphism (hom), isomorphism (iso), or identity isomorphism (ids)]						
	PSF_S1 XY-S1 XY-S2 XY-S3	PSF_S2 XY-S1 XY-S2	PSF_S3 XY-S1	PSF_S4 XY-S2	PSF_S5 XY-S1 XY-S3	PSF_S6 XY-S2 XY-S3	PSF_S7 XY-S3
SD1							
VM1	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids
VM2	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom
VM3	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids
VM4	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom
VM5	-	-	-	-	-	-	L1 par hom
VM6	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM7	-	L1 hom	L1 hom	L1 hom	-	-	-
VM8	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM9	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM10	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM11	-	L1 hom	L1 hom	L1 hom	-	-	-
VM12	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM13	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM14	-	-	-	-	-	-	L1 par hom
VM15	-	-	-	-	-	-	L1 par hom

VM16	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso
VM17	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso
VM18	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso

4.7.2 VM defined from SD2

Table 79 provides a summary of the results, which are substantiation by the supporting results captured in the Appendix (7.12).

Table 79: Summary results of definition of verification models (VM) from SD2

VM#	Defined with respect to SD and described as [L1 and/or L2] [parameter] and/or [homomorphism (hom), isomorphism (iso), or identity isomorphism (ids)]						
	PSF_S1 XY-S1 XY-S2 XY-S3	PSF_S2 XY-S1 XY-S2	PSF_S3 XY-S1	PSF_S4 XY-S2	PSF_S5 XY-S1 XY-S3	PSF_S6 XY-S2 XY-S3	PSF_S7 XY-S3
SD2							
VM1	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom
VM2	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids
VM3	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom
VM4	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids
VM5	-	-	-	-	-	-	L1 par hom
VM6	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM7	-	L1 hom	L1 hom	L1 hom	-	-	-
VM8	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM9	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM10	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM11	-	L1 hom	L1 hom	L1 hom	-	-	-
VM12	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM13	-	L1 par hom	L1 par hom	L1 par hom	-	-	-

VM14	-	-	-	-	-	-	L1 par hom
VM15	-	-	-	-	-	-	L1 par hom
VM16	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom
VM17	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom
VM18	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom

4.7.3 VM defined from SD3

Table 80 provides a summary of the results, which are substantiation by the supporting results captured in the Appendix (7.12).

Table 80: Summary results of definition of verification models (VM) from SD3

VM#	Defined with respect to SD and described as [L1 and/or L2] [parameter] and/or [homomorphism (hom), isomorphism (iso), or identity isomorphism (ids)]						
	PSF_S1 XY-S1 XY-S2 XY-S3	PSF_S2 XY-S1 XY-S2	PSF_S3 XY-S1	PSF_S4 XY-S2	PSF_S5 XY-S1 XY-S3	PSF_S6 XY-S2 XY-S3	PSF_S7 XY-S3
SD3							
VM1	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids
VM2	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom
VM3	L2 par ids	L2 par ids	L2 par ids	L2 par ids	L2 par ids	L2 par ids	L2 par ids
VM4	L2 par hom	L2 par hom	L2 par hom	L2 par hom	L2 par hom	L2 par hom	L2 par hom
VM5	-	-	-	-	-	-	L1 par hom
VM6	-	L2 par hom	L2 par hom	L2 par hom	-	-	-
VM7	-	L1 hom	L1 hom	L1 hom	-	-	-
VM8	-	L2 par hom	L2 par hom	L2 par hom	-	-	-
VM9	-	L2 par hom	L2 par hom	L2 par hom	-	-	-
VM10	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM11	-	L1 hom	L1 hom	L1 hom	-	-	-

VM12	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM13	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM14	-	-	-	-	-	-	L1 par hom
VM15	-	-	-	-	-	-	L1 par hom
VM16	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso
VM17	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso
VM18	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso	L1 par iso

4.7.4 VM defined from SD4

Table 81 provides a summary of the results, which are substantiation by the supporting results captured in the Appendix (7.12).

Table 81: Summary results of definition of verification models (VM) from SD4

VM#	Defined with respect to SD and described as [L1 and/or L2] [parameter] and/or [homomorphism (hom), isomorphism (iso), or identity isomorphism (ids)]						
	PSF_S1 XY-S1 XY-S2 XY-S3	PSF_S2 XY-S1 XY-S2	PSF_S3 XY-S1	PSF_S4 XY-S2	PSF_S5 XY-S1 XY-S3	PSF_S6 XY-S2 XY-S3	PSF_S7 XY-S3
SD4							
VM1	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom
VM2	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids	L1 par ids
VM3	L2 par hom	L2 par hom	L2 par hom	L2 par hom	L2 par hom	L2 par hom	L2 par hom
VM4	L2 par ids	L2 par ids	L2 par ids	L2 par ids	L2 par ids	L2 par ids	L2 par ids
VM5	-	-	-	-	-	-	L1 par hom
VM6	-	L2 par hom	L2 par hom	L2 par hom	-	-	-
VM7	-	L1 hom	L1 hom	L1 hom	-	-	-
VM8	-	L2 par hom	L2 par hom	L2 par hom	-	-	-
VM9	-	L2 par hom	L2 par hom	L2 par hom	-	-	-

VM10	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM11	-	L1 hom	L1 hom	L1 hom	-	-	-
VM12	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM13	-	L1 par hom	L1 par hom	L1 par hom	-	-	-
VM14	-	-	-	-	-	-	L1 par hom
VM15	-	-	-	-	-	-	L1 par hom
VM16	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom
VM17	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom
VM18	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom	L1 par hom

4.8 VM that adhere to VMMC

The results are based on the VMMC defined in the methods chapter and the previous section providing proof of VM definition from SD. Each section provides a summary table of the VM that adhere to the VMMC.

4.8.1 VM that adhere to VMMC1

Table 82 provides a summary of the VM that adhere to this set of VMMC.

Table 82: Summary results of definition of verification models (VM) that adherence to the verification model morphic conditions (VMMC1)

VM#	Defined from VMMC1 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	Yes	-	Yes	-
VM2	-	Yes	-	Yes
VM3	Yes	-	Yes	-
VM4	-	Yes	-	Yes
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-

VM15	-	-	-	-
VM16	Yes	-	Yes	-
VM17	Yes	-	Yes	-
VM18	Yes	-	Yes	-

4.8.2 VM that adhere to VMMC2

Table 83 provides a summary of the VM that adhere to this set of VMMC.

Table 83: Summary results of definition of verification models (VM) that adherence to the verification model morphic conditions (VMMC2)

VM#	Defined from VMMC2 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	Yes	-
VM4	-	-	-	Yes
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.8.3 VM that adhere to VMMC3

Table 84 provides a summary of the VM that adhere to this set of VMMC.

Table 84: Summary results of definition of verification models (VM) that adherence to the verification model morphic conditions (VMMC3)

VM#	Defined from VMMC3 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	Yes	Yes
VM4	-	-	Yes	Yes
VM5	-	-	-	-
VM6	-	-	Yes	Yes

VM7	-	-	-	-
VM8	-	-	Yes	Yes
VM9	-	-	Yes	Yes
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.8.4 VM that adhere to VMMC4

Table 85 provides a summary of the VM that adhere to this set of VMMC.

Table 85: Summary results of definition of verification models (VM) that adherence to the verification model morphic conditions (VMMC4)

VM#	Defined from VMMC4 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	Yes	Yes	Yes	Yes
VM2	Yes	Yes	Yes	Yes
VM3	Yes	Yes	Yes	Yes
VM4	Yes	Yes	Yes	Yes
VM5	Yes	Yes	Yes	Yes
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	Yes	Yes	Yes	Yes
VM15	Yes	Yes	Yes	Yes
VM16	Yes	Yes	Yes	Yes
VM17	Yes	Yes	Yes	Yes
VM18	Yes	Yes	Yes	Yes

4.8.5 VM that adhere to VMMC5

Table 86 provides a summary of the VM that adhere to this set of VMMC.

Table 86: Summary results of definition of verification models (VM) that adherence to the verification model morphic conditions (VMMC5)

VM#	Defined from VMMC5 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	Yes	-	Yes	-
VM2	-	Yes	-	Yes
VM3	Yes	-	Yes	-
VM4	-	Yes	-	Yes
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	Yes	-	Yes	-
VM17	-	-	-	-
VM18	Yes	-	Yes	-

4.8.6 VM that adhere to VMMC6

Table 87 provides a summary of the VM that adhere to this set of VMMC.

Table 87: Summary results of definition of verification models (VM) that adherence to the verification model morphic conditions (VMMC6)

VM#	Defined from VMMC6 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	Yes	Yes	Yes	Yes
VM2	Yes	Yes	Yes	Yes
VM3	Yes	Yes	Yes	Yes
VM4	Yes	Yes	Yes	Yes
VM5	-	-	-	-
VM6	Yes	Yes	Yes	Yes
VM7	Yes	Yes	Yes	Yes
VM8	Yes	Yes	Yes	Yes
VM9	Yes	Yes	Yes	Yes
VM10	Yes	Yes	Yes	Yes
VM11	Yes	Yes	Yes	Yes
VM12	Yes	Yes	Yes	Yes
VM13	Yes	Yes	Yes	Yes
VM14	-	-	-	-

VM15	-	-	-	-
VM16	Yes	Yes	Yes	Yes
VM17	Yes	Yes	Yes	Yes
VM18	Yes	Yes	Yes	Yes

4.9 VM defined from combination of VRPS, VMMC, and SD

This section provides the results from defining VM based on a combination of relationships to VRPS, VMMC, and SD.

4.9.1 VM defined from combination of VRPS1, VMMC, and SD

4.9.1.1 VRPS1, VMMC1, and SD

Table 88 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 88: Summary results of VM defined from combination of VRPS1, VMMC1, and SD

VM#	Defined from VRPS1 and VMMC1 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.1.2 VRPS1, VMMC2, and SD

Table 89 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 89: Summary results of VM defined from combination of VRPS1, VMMC2, and SD

VM#	Defined from VRPS1 and VMMC2 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4

VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.1.3 VRPS1, VMMC3, and SD

Table 90 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 90: Summary results of VM defined from combination of VRPS1, VMMC3, and SD

VM#	Defined from VRPS1 and VMMC3 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-

VM17	-	-	-	-
VM18	-	-	-	-

4.9.1.4 VRPS1, VMMC4, and SD

Table 91 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 91: Summary results of VM defined from combination of VRPS1, VMMC4, and SD

VM#	Defined from VRPS1 and VMMC4 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.1.5 VRPS1, VMMC5, and SD

Table 92 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 92: Summary results of VM defined from combination of VRPS1, VMMC5, and SD

VM#	Defined from VRPS1 and VMMC5 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-

VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.1.6 VRPS1, VMMC6, and SD

Table 93 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 93: Summary results of VM defined from combination of VRPS1, VMMC6, and SD

VM#	Defined from VRPS1 and VMMC6 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	Yes	Yes	Yes	Yes
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.2 VM defined from combination of VRPS2, VMMC, and SD

4.9.2.1 VRPS2, VMMC1, and SD

Table 94 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 94: Summary results of VM defined from combination of VRPS2, VMMC1, and SD

VM#	Defined from VRPS2 and VMMC1 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	Yes	-	Yes	-
VM2	-	Yes	-	Yes
VM3	Yes	-	Yes	-
VM4	-	Yes	-	Yes
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	Yes	-	Yes	-
VM17	Yes	-	Yes	-
VM18	Yes	-	Yes	-

4.9.2.2 VRPS2, VMMC2, and SD

Table 95 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 95: Summary results of VM defined from combination of VRPS2, VMMC2, and SD

VM#	Defined from VRPS2 and VMMC2 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	Yes	-
VM4	-	-	-	Yes
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-

VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.2.3 VRPS2, VMMC3, and SD

Table 96 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 96: Summary results of VM defined from combination of VRPS2, VMMC3, and SD

VM#	Defined from VRPS2 and VMMC3 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	Yes	Yes
VM4	-	-	Yes	Yes
VM5	-	-	-	-
VM6	-	-	Yes	Yes
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.2.4 VRPS2, VMMC4, and SD

Table 97 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 97: Summary results of VM defined from combination of VRPS2, VMMC4, and SD

VM#	Defined from VRPS2 and VMMC4 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	Yes	Yes	Yes	Yes
VM2	Yes	Yes	Yes	Yes
VM3	Yes	Yes	Yes	Yes
VM4	Yes	Yes	Yes	Yes
VM5	-	-	-	-
VM6	-	-	-	-

VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	Yes	Yes	Yes	Yes
VM17	-	-	-	-
VM18	Yes	Yes	Yes	Yes

4.9.2.5 VRPS2, VMMC5, and SD

Table 98 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 98: Summary results of VM defined from combination of VRPS2, VMMC5, and SD

VM#	Defined from VRPS2 and VMMC5 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	Yes	-	Yes	-
VM2	-	Yes	-	Yes
VM3	Yes	-	Yes	-
VM4	-	Yes	-	Yes
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	Yes	-	Yes	-
VM17	-	-	-	-
VM18	Yes	-	Yes	-

4.9.2.6 VRPS2, VMMC6, and SD

Table 99 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 99: Summary results of VM defined from combination of VRPS2, VMMC6, and SD

VM#	Defined from VRPS2 and VMMC6 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	Yes	Yes	Yes	Yes
VM2	Yes	Yes	Yes	Yes
VM3	Yes	Yes	Yes	Yes
VM4	Yes	Yes	Yes	Yes
VM5	-	-	-	-
VM6	Yes	Yes	Yes	Yes
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	Yes	Yes	Yes	Yes
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	Yes	Yes	Yes	Yes
VM17	-	-	-	-
VM18	Yes	Yes	Yes	Yes

4.9.3 VM defined from combination of VRPS3, VMMC, and SD

4.9.3.1 VRPS3, VMMC1, and SD

Table 100 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 100: Summary results of VM defined from combination of VRPS3, VMMC1, and SD

VM#	Defined from VRPS3 and VMMC1 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	Yes	-	Yes	-
VM2	-	Yes	-	Yes
VM3	Yes	-	Yes	-
VM4	-	Yes	-	Yes
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-

VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.3.2 VRPS3, VMMC2, and SD

Table 101 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 101: Summary results of VM defined from combination of VRPS3, VMMC2, and SD

VM#	Defined from VRPS3 and VMMC2 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	Yes	-
VM4	-	-	-	Yes
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.3.3 VRPS3, VMMC3, and SD

Table 102 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 102: Summary results of VM defined from combination of VRPS3, VMMC3, and SD

VM#	Defined from VRPS3 and VMMC3 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	Yes	Yes
VM4	-	-	Yes	Yes

VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.3.4 VRPS3, VMMC4, and SD

Table 103 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 103: Summary results of VM defined from combination of VRPS3, VMMC4, and SD

VM#	Defined from VRPS3 and VMMC4 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	Yes	Yes	Yes	Yes
VM2	Yes	Yes	Yes	Yes
VM3	Yes	Yes	Yes	Yes
VM4	Yes	Yes	Yes	Yes
VM5	Yes	Yes	Yes	Yes
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.3.5 VRPS3, VMMC5, and SD

Table 104 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 104: Summary results of VM defined from combination of VRPS3, VMMC5, and SD

VM#	Defined from VRPS3 and VMMC5 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	Yes	-	Yes	-
VM2	-	Yes	-	Yes
VM3	Yes	-	Yes	-
VM4	-	Yes	-	Yes
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.3.6 VRPS3, VMMC6, and SD

Table 105 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 105: Summary results of VM defined from combination of VRPS3, VMMC6, and SD

VM#	Defined from VRPS3 and VMMC6 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	Yes	Yes	Yes	Yes
VM2	Yes	Yes	Yes	Yes
VM3	Yes	Yes	Yes	Yes
VM4	Yes	Yes	Yes	Yes
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-

VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.4 VM defined from combination of VRPS4, VMMC, and SD

4.9.4.1 VRPS4, VMMC1, and SD

Table 106 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 106: Summary results of VM defined from combination of VRPS4, VMMC1, and SD

VM#	Defined from VRPS4 and VMMC1 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.4.2 VRPS4, VMMC2, and SD

Table 107 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 107: Summary results of VM defined from combination of VRPS4, VMMC2, and SD

VM#	Defined from VRPS4 and VMMC2 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-

VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.4.3 VRPS4, VMMC3, and SD

Table 108 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 108: Summary results of VM defined from combination of VRPS4, VMMC3, and SD

VM#	Defined from VRPS4 and VMMC3 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	Yes	Yes
VM9	-	-	Yes	Yes
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.4.4 VRPS4, VMMC4, and SD

Table 109 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 109: Summary results of VM defined from combination of VRPS4, VMMC4, and SD

VM#	Defined from VRPS4 and VMMC4 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.4.5 VRPS4 VMMC5, and SD

Table 110 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 110: Summary results of VM defined from combination of VRPS4, VMMC5, and SD

VM#	Defined from VRPS4 and VMMC5 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-

VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.4.6 VRPS4, VMMC6, and SD

Table 111 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 111: Summary results of VM defined from combination of VRPS4, VMMC6, and SD

VM#	Defined from VRPS4 and VMMC6 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	Yes	Yes	Yes	Yes
VM9	Yes	Yes	Yes	Yes
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.5 VM defined from combination of VRPS5, VMMC, and SD

4.9.5.1 VRPS5, VMMC1, and SD

Table 112 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 112: Summary results of VM defined from combination of VRPS5, VMMC1, and SD

VM#	Defined from VRPS5 and VMMC1 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-

VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.5.2 VRPS5, VMMC2, and SD

Table 113 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 113: Summary results of VM defined from combination of VRPS5, VMMC2, and SD

VM#	Defined from VRPS5 and VMMC2 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.5.3 VRPS5, VMMC3, and SD

Table 114 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 114: Summary results of VM defined from combination of VRPS5, VMMC3, and SD

VM#	Defined from VRPS5 and VMMC3 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.5.4 VRPS5, VMMC4, and SD

Table 115 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 115: Summary results of VM defined from combination of VRPS5, VMMC4, and SD

VM#	Defined from VRPS5 and VMMC4 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-

VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.5.5 VRPS5, VMMC5, and SD

Table 116 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 116: Summary results of VM defined from combination of VRPS5, VMMC5, and SD

VM#	Defined from VRPS5 and VMMC5 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-
VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	-	-	-	-
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.9.5.6 VRPS5, VMMC6, and SD

Table 117 summarizes the VM that may be defined based on the select combination of VRPS, VMMC, and SD.

Table 117: Summary results of VM defined from combination of VRPS5, VMMC6, and SD

VM#	Defined from VRPS5 and VMMC6 with respect to SD[#]? [Yes/-]			
	SD1	SD2	SD3	SD4
VM1	-	-	-	-
VM2	-	-	-	-

VM3	-	-	-	-
VM4	-	-	-	-
VM5	-	-	-	-
VM6	-	-	-	-
VM7	Yes	Yes	Yes	Yes
VM8	-	-	-	-
VM9	-	-	-	-
VM10	-	-	-	-
VM11	-	-	-	-
VM12	-	-	-	-
VM13	-	-	-	-
VM14	-	-	-	-
VM15	-	-	-	-
VM16	-	-	-	-
VM17	-	-	-	-
VM18	-	-	-	-

4.10 Forming of and Discussion on the Resultant Systems Theoretic Metamodel of Verification Artifacts

This section is intended to tie the previous results sections together through discussion of the results, the formation of a resultant metamodel, and the comparison of the results to the state of SE practice. As such, the first section provides a discussion on the implications of the defining of VM from SR; the defining of VM from VRPS; the defining of VM from SD; and the defining of VM from the combination of VRPS, SD, and VMMC. From this discussion stems the second section, which documents the resultant metamodel and describes an approach to its practical application. Lastly, the third section validates the uniqueness of the metamodel through comparison to the state of SE practice.

4.10.1 Discussion of relational definition of VM

Overall, the results suggest that VM should be defined on the basis of a combination of relationship to SR, VRPS, SD, and the VMMC conditions of representativeness. The results of the exploration of the assumptions of orthogonality in SR suggests that consequences exist. For example, any VM that was water-resistant adhered to the water-resistance subset of SR. Furthermore, in the water-resistant VRPS3 verification, the set of VM that adhered to VRPS3 was reduced to only those VM that were within the range of the parameterization of the SD. And, when adding the morphic equivalence of VM to SD and the VMMC, the acceptability of the VM was further reduced and case specific to the combination. From this, the relational definition of VM is suggested to be indirectly defined on the basis of SR (through VRPS), directly defined on the basis of equivalence to SD, and directly defined on the basis of VR that consist of VRPS and VMMC.

Further explanation is provided in the remainder of this subsection.

4.10.1.1 VM defined from SR

Because VM1, VM2, VM3, and VM4 corresponding to the same numbered SD, it was expected that these VM may be defined from the superset of SR. Although, not intentional, the submarine with a yellow-light, VM18, was also defined on the basis of the superset of SR. As discussed in the methods chapter, much of the SR was defined with the intention of opening the design space to solution systems, which explains why VM18 was proven to have the ability to be defined on the basis of the superset of SR.

The VM defined on the basis of the on/off/yellow-light functionality of XY-S1 and XY-S2 provided results that were expected. All of the SD based VM were proven to be defined on the basis of this subset of SR. VM6, which was based on coupling of the light functionality components of SD3, was also proven to adhere to this subset of SR. What was unexpected in the case of this functionality was that the firefly-based VM (VM12 and VM16) were not defined on the basis of XY-S1 and the radio-based VM (VM13 and VM17) were not defined on the basis of XY-S2. These VM were created specifically with exploration of the orthogonality of SR in mind and originally believed to adhere to this subset of SR. However, this unexpected result is due to strict interpretation of symbolic instantiation, meaning that the 'on-trigger' of the firefly could have been interpreted as equal to the 'on-command' of the SR and, in which case, the firefly-based VM could have been defined on the basis of this subset of SR. In other words, if the parameterization of the IoX, in this case, were the criteria for adherence to the SR, then the firefly and radio VM would have adhered to the correspond SR subsets. For example, the firefly in a dry-bag would have adhered to the superset of SR. This may change the results; however, it would not change the outcome of the question.

The VM defined on the basis of the water-resistance functional of XY-S3 provide mostly intuitive results. Effectively, any of the VM that provide water-resistance functionality were defined on the basis of this subset of VM. Some of the potentially counter-intuitive VM defined here were the dry-bag (VM15), fireflies in a dry-bag (VM16), and water-proof radio (VM17). The counter-intuitive aspect to this may be because there exist an assumed, pre-existing notion of equivalence between the VM and the SD, which suggests that these VM may not have the equivalence desired. For example, in viewing the SR superset, we know that the system must produce light and be water-resistant; which we may heuristically assume to be the SR for a water-proof flashlight that is not equivalent to a dry-bag, firefly, or radio.

4.10.1.2 VM defined from VRPS

Recall that VRPS1 was intentionally defined to be a counter-intuitive problem space and with the pizza VM (VM11) in mind. It was expected that VM11 would be defined on the basis of VRPS1. Furthermore, it was expected that no other VM would be defined on the basis of VRPS1. However, at the onset of this research, it was unexpected that VRPS1 would have morphic equivalence to the SR. It the process of defining the research path, it was discovered that there existed a common underlying mathematical structure. Although not the main exploration path of this dissertation, defining of VRPS on the basis of SR should be explored further.

Where the previous section discussed VM defined on the basis of on/light function separate from the off/no-light function, VRPS2 explored the definition of VM based on the combined functions and associated interfaces. In this case, it was expected that all the SD-based VM would be defined on the basis of VRPS2 as well as the submarine (VM18). The remainder of the VM were not expected to be defined on the basis of VRPS1.

The VRPS3 was designed based on the SR subset for water-resistance; however, parameterization of the water IF was added. Without this addition, the results of the definition of VM on the basis of VRPS3 would have been the same as on the basis of the water-resistance subset of SR. The VM that were eliminated were all of the VM that were not based explicitly on one of the SD. For example, the fireflies in a dry-bag (VM16), water-proof hand-radio (VM17), and the submarine (VM18) were all proven to not adhere to VRPS3. Note, the range of the parameterization of the water IF is consistent with the range of the IF for the SD-based VM. An implication here is that some, perhaps implicit, knowledge of the parameterization of the SD may be present.

The VRPS4 was designed with the intention of the only acceptable VM being those that provide a blue-light, versus the yellow-light defined in the SR. The outcome of defining VM on the basis of VRPS4 was expected to yield only those VM that provide blue-light, which was VM8 and VM9.

The VRPS5 was designed with the intention of the only acceptable VM being those that exchange 1's and 0's, versus the on/off/light functions defined in the SR. The outcome of defining VM on the basis of VRPS5 was expected to yield only those VM that exchange 1's and 0's, which was VM7.

4.10.1.3 VM defined from SD

For the VM defined on the basis of SD, the results suggest that every VM may be defined on the basis of every SD. This was due to the fact that each VM had some morphic equivalence to every SD. At the onset of this research, it was not intended or known that each VM would have morphic equivalence. As the research progressed, it became clear that each VM and SD had some commonality in underlying mathematical structure. As a result, the morphic equivalence could be used in terms of that common mathematical structure of the SM with the addition of the instantiation of the SM through symbolism and parameterization. This was particularly unexpected for the pizza VM, VM11; which was intentionally selected due to an initial belief that there is no morphic equivalence to a flashlight. However, the consistency in morphic equivalence of the SD and all VM could be due to the limited focus on simple, discrete systems. And, had the selection been on continuous systems, the morphic equivalence may not hold; for example, between a pizza and a flashlight.

4.10.1.4 VM defined from combo

The combination includes the addition of the VMMC along with the SD morphisms and the VRPS. The SR defined VM were not included in this section. The VM defined here are the intersection of the VM that adhere to the specific VRPS, are morphically equivalent to specific SD, and the morphic equivalence adheres to the specific VMMC.

What was anticipated was to see a changed in the acceptability of VM based on defining VM from individual relationships versus the combination of relationship. This change in the acceptability of VM, indeed, occurred. However, unexpectedly, there were many cases in which zero VM were acceptable. This suggests that an alignment between the combination may warrant further exploration; although, this was not necessary to address the current research question. And, overall, the results of this means of defining VM suggest that VM should be defined on the basis of the combination of relationships between VRPS, VMMC, and SD.

4.10.2 Metamodel

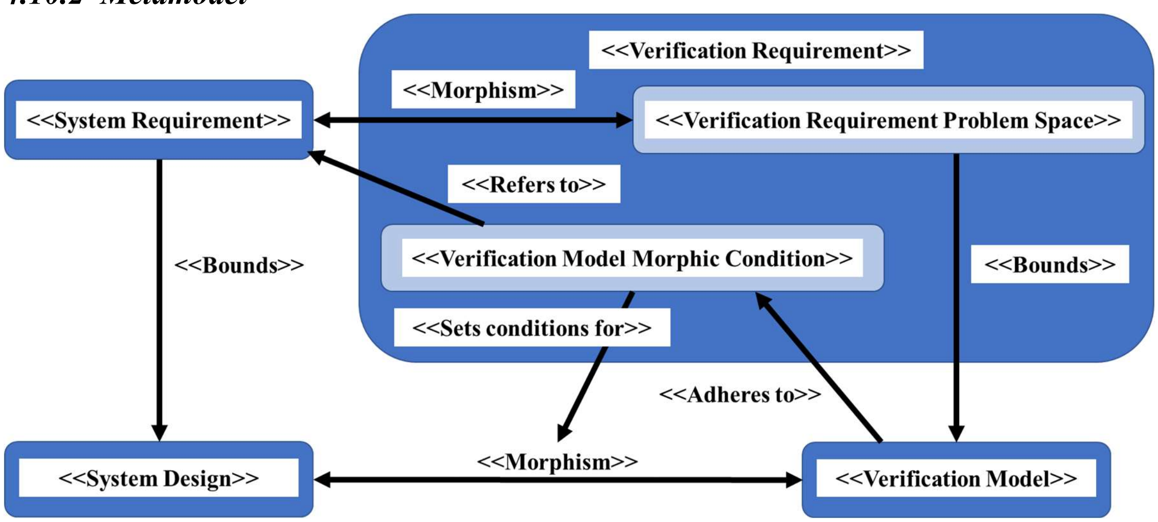

Figure 21: Wymorian Systems Engineering (WySE) metamodel of verification artifacts resultant from this dissertation

A resultant from this dissertation research is the Wymorian Systems Engineering (WySE) metamodel of verification artifacts, which is shown below in Figure 21. The taxonomy is defined in Table 118. Note, the metamodel should also be used in conjunction with the taxonomy and methods provided in the Methods chapter of this dissertation.

Table 118: Description of elements and relationships in the Wymorian Systems Engineering (WySE) metamodel of verification artifacts

Term	Description
Adheres to	• A relationship that links the desired pedigree defined by the VMMC with VM that adhere to the desired pedigree
Bounds	• A relationship that links problem spaces with system models (i.e., SD and VM) that are within the solution space
Morphism	• A mathematical characterization of preservation of equivalence between pairs of system specifications

Refers to	• A relationship that links attributes of the SR to VMMC such as functions and parameters
Sets conditions for	• A relationship that links the conditions for equivalence to the morphism between the SD and VM
System Design	• A system specification defined at L1 or L2 that is considered to be the system of interest/innovation, which is bound by the problem space established by the SR
System Requirement	• A problem space of functions that bounds the acceptability of SD
Verification Model	• A system specification defined at L1 or L2 which is deemed acceptably defined only if it is (1) bound by the problem space established by a VRPS, (2) has morphic equivalence to SD, and (3) adheres to the VMMC
Verification Model Morphic Condition	• Defines the desired conditions for morphic equivalence between SD and VM
Verification Requirement	• Consists of VRPS and VMMC
Verification Requirement Problem Space	• A problem space of functions defined at L0 that bounds the acceptability of VM and has morphic equivalence to SR

4.10.3 Validation of metamodel compared to SE practice

Per the methods, the WySE metamodel was compared to that state of SE practice to confirm uniqueness and contribution of the research. This was accomplished through comparing the WySE metamodel to SysML as defined in [3, 45] and the collection of SE expertise as defined in [42]. Each of the three were characterized in accordance with the defined methodology from the Methods chapter and conclusion meaning is summarized in the final subsection.

4.10.3.1 Assessment of WySE Metamodel of Verification Artifacts

Table 119 shows the characterize of the WySE metamodel. In this case, the VM have an indirect relationship to SR, direct relationship to VRPS, and direct relationship to SD. Furthermore, the VM relationship to SR is explicit, the VM relationship to VRPS is explicit, the VM relationship to SD is explicit, and the VM pedigree is explicit. Lastly, all relationships are defined mathematically in accordance with Wymorian systems theory, which means they are inherently quantitative/analytical.

Table 119: Results of the assessment of the WySE metamodel of verification artifacts

WySE	SR-VM	VRPS-VM	SD-VM	VM fidelity/pedigree
Direct, Indirect, Minimally Observed (M/O),	Indirect	Direct	Direct	N/A

or Not Applicable (N/A)				
Implicit, Explicit, or Not Observed (N/O)	Explicit	Explicit	Explicit	Explicit
(Qualitative, descriptive) (Quantitative, analytical), or Not Observed (N/O)	Quantitative, analytical	Quantitative, analytical	Quantitative, analytical	Quantitative, analytical

4.10.3.2 Assessment of SysML

Table 120 shows the characterize of SysML. In this case, the VM have a direct relationship to SR, direct relationship to VRPS, and minimally observed relationship to SD. Furthermore, the VM relationship to SR is explicit, the VM relationship to VRPS is explicit, the VM relationship to SD is explicit, and the VM fidelity/pedigree is minimally observed. Lastly, all relationships are descriptive/qualitative definitions.

Of particular note here is the assessment of minimally observed for the SD-VM relationship and the definition of fidelity/pedigree. As discussed in previous sections, the "test case" serves the intent of defining the VRPS and use of a VM. Defining of a VM does not appear to be required for SysML; and, in [3], the VM is the SD. Additionally, there is not an inherent, explicit relationship between SD and VM in SysML. Furthermore, the "test case" has a direct relationship ("verify") to system requirements, which suggests assumed orthogonality.

Table 120: Results of the assessment of SysML

SysML	SR-VM	VRPS-VM	SD-VM	VM fidelity/pedigree
Direct, Indirect, Minimally Observed (M/O), or Not Applicable (N/A)	Direct	Direct	M/O	N/A
Implicit, Explicit, or Minimally Observed (M/O)	Explicit	Explicit	Implicit	M/O
(Qualitative, descriptive) (Quantitative, analytical), or Not Observed (N/O)	Qualitative, descriptive	Qualitative, descriptive	Qualitative, descriptive	Qualitative, descriptive

4.10.3.3 Assessment of SE subject matter expertise

Table 121 shows the characterize based on SE subject matter expertise. In this case, the VM have a direct relationship to SR, direct relationship to VRPS, and minimally observed relationship to SD. Furthermore, the VM relationship to SR is explicit, the VM relationship to VRPS is implicit, the VM relationship to SD is implicit, and the VM fidelity/pedigree is minimally observed. Lastly, all relationships are descriptive/qualitative definitions.

Similar to SysML, the SE subject matter expertise provides a minimally observed definition of VM on the basis of SD. Even through fidelity of VM may be stated, the definition is qualitative and not mandatory. This suggests that the representativeness of VM and relationship to SD is implicit. Furthermore, the VM are suggested to be defined to confirm a specific function from the SR, which suggests a direct relationship between SR and VM; and, the VM are suggested to defined based on the specific verification activity, which suggests an indirect relationship between VM and SR through the VRPS. This suggests that the experts implicitly perceive that the VM may be defined as either a direct or indirect relationship to SR; and, thus, there is potential assumption of orthogonality.

Table 121: Results of the assessment of SE subject matter expertise

Applied Space Systems Engineering [42]	SR-VM	VRPS-VM	SD-VM	VM fidelity/pedigree
Direct, Indirect, Minimally Observed (M/O), or Not Applicable (N/A)	Direct/Indirect	Direct	M/O	N/A
Implicit, Explicit, or Minimally Observed (M/O)	Explicit	Explicit	Implicit	Implicit
(Qualitative, descriptive) (Quantitative, analytical), or Not Observed (N/O)	Qualitative, descriptive	Qualitative, descriptive	Qualitative, descriptive	Qualitative, descriptive

4.10.3.4 Meaning of comparison

Overall, the comparison of the WySE metamodel, produced as part of this dissertation, to the state of SE practice, as characterize based on SysML and SE subject matter expertise, reveals a unique contribution of the body of research of this dissertation. The current state of SE practice is largely limited to qualitative definition of VM. Although not stated as part of the assessment above, it was confirmed that verification requirements are not typically specified mathematically. The results of the comparison suggest that it is typical of the state of SE practice to assume orthogonality of SR, which is accounted for in the WySE metamodel through the combined relationships that provide a normative approach to accounting to orthogonality assumptions. For example, the use of the blue-light VM (VM8 and VM9) can be deemed acceptable given it is within the intersection of the morphic equivalence to SD, the morphic equivalence adhere to the VMMC, and the adherence to VRPS (e.g., VRPS4-VMMC6-SD combo). Furthermore, the results of the comparative assessment suggest that it is generally not expected that VM representativeness be characterized, which is accounted for mathematically in the WySE metamodel through the use of system morphisms. This suggests that a research gap has been identified and has begun to be addressed through this dissertation body of research, which will subsequently advance the state of the practice and discipline of SE.

5 Conclusion

This chapter provides discussion on the contributions of the research, followed by discussion of the limitations resulting from the methods used to address the research question, and concludes with discussion on future research opened by this dissertation.

5.1 Contributions

The section documents the contributions of this dissertation. The contributions were confirmed through extensive review of the literature as well as comparison of the resultant metamodel to the state of SE practice in the final section of the results. The contributions are listed below:

1. This research advances verification research, which is known to have limited attention and to be in need of theoretical foundations.
2. This research uniquely defines verification requirements on the basis of systems theory, rather than qualitative documentation.
3. This research uniquely defines verification model representativeness to a system design on the basis of systems theoretic morphic equivalence, rather than qualitative, heuristic assumptions.
4. This research addresses the assumption of orthogonality through exploring systems theoretic relationships used to define verification models.
5. Lastly, from the above, this research advances theoretical foundations for SE, which is known to be desired by the SE community.

5.2 Limitations

Topics of limitations of this research are listed below, followed by further elaboration.

1. The research is based on simple systems.
2. The research used the set theoretic IOFO of DEVS versus topology for the mathematical basis of the problem spaces of functions and morphisms.
3. The research revealed a difference in some of the DEVS-based simulations versus the T3SD-basd tabular definitions.

In regard to topic one, the research is based on discrete, deterministic, open systems. Additionally, each mathematical structure was simple in the sense that each had a rather small number of items in each set within the structure. For example, the notion of a two-state flashlight is considered to be a simple system. This simplicity was considered necessary due to the manual nature required to conduct the research and sufficient to address the research question. However, some potentially counter-intuitive results are likely due to the simplicity. For example, the pizza related verification artifacts were intentionally created due to an initial intuitive thought that there should not be equivalence between a pizza and a flashlight. However, the results suggest that equivalence exists between the pizza and the flashlight. Should the pizza and flashlight be based on the physics of continuous systems, the equivalence may not hold. While this may change the results, it should not change the outcome of the answer to the research question.

In regard to topic two, the research leverages set theory versus topology. The notion of a problem space stems from topology, which is the basis for problem spaces of functions. A simplification was made for this research to use the set theoretic IOFO of DEVS, which enabled the use of tabular proof of morphisms, based on the IOFO morphism, between SR and VRPS. Ideally, the proof of morphism between the SR and VRPS would have been on the basis of the topological definition of a homeomorphism, rather than set theoretic homomorphism. However, the equivalence between the SR and VRPS is expected to hold, the results should not change, and the outcome of the answer to the research question should not change.

In regard to topic three, the T3SD-based tabular results were validated through use of DEVS-based simulation. The mathematical structures for specification of systems models between T3SD and DEVS are slightly different. Both are based on the notion of a Moore-type state machine. However, the DEVS structures contain time advance considerations, which are not inherent the T3SD structures leveraged. The distinction became apparent when validated the level 2 coupled component systems with simultaneous outputs with the DEVS-based simulation in MS4 Me. In the T3SD-based tabular format, the systems assumed simultaneous output; however, the initial DEVS-based simulation models did not produce outputs simultaneously. This was due to the fact that all "real" systems have delays between transformations of inputs into outputs, which was implicitly assumed in the T3SD-based tabular form and not accounted for in the initial DEVS-based simulation. This was addressed by adding a time delay to the two back-end (output providing) components, which synchronized the outputs. Although this is an item to consider for future research, this limitation did not change the results or change the outcome of the answer to the research question.

In research process more complex systems were considered, such as Arduino and LEGO based robotics; however, the

5.3 Future work

Topics of future research that were opened based on this dissertation are listed below as example questions, which is followed by further elaboration.

1. To what extent does context matter?
2. To what extent may the methods be extended to characterize validation models?
3. To what extent may the methods be extended to continuous and probabilistic systems?
4. What types of verification requirements exist?
5. When should verification requirements be defined?
6. To what extent do the methods reduce risk stemming from verification planning?
7. To what extent does qualitative fidelity proposed for verification models in early phases hold when compared to the final product?
8. To what extent may the methods be extended to characterize the dynamic relationship between requirements, design, and verification?

9. What other systems theoretic morphisms exist that may be leveraged to extend this body of research?
10. To what extent may the process be automated?

In regard to topic one, the results suggest that context may matter; however, the equivalence of underlying mathematical structures defined on the basis of systems theory suggest existence of domain independence. Essentially, the precision of the acceptability of the verification models may be manipulated based on the verification requirement problem space and the specificity of verification model morphic conditions, which may provide indication of desiring specificity that is the same as (equal to) or some level of equivalence to the problem space defined by the system requirements and the system design. This may be used to create measured manipulation the context of both the underlying mathematical structures and their instantiation. Confidence may be measured based on the knowledge of the context, which may be defined through qualitative assumption, qualitative documentation, and quantitative system specification as with this dissertation. To measure the extent to which context matter, it is recommended to leveraged Bayesian and utility-driven methods such as those proposed in [33, 34].

In regard to topic two, the research in this dissertation was limited to verification of adherence to system requirement problem spaces of functions; however, there may exist extensions to characterize validation of adherence to stakeholder needs problem spaces of outcomes. Open systems are defined on the basis of problem spaces of functions and closes systems are defined on the basis of problem spaces of outcomes [38]. This dissertation leveraged systems theoretic mechanisms for problem spaces of functions and open systems. It is currently unknown as to the extent to which the methods may be extended to problem spaces of outcomes and closed systems; however, alternate DEVS systems theoretic formalisms exist (e.g., chapter 21 of [73]), which may potentially be leveraged to address this research.

In regard to topic three, to complement topic two, the research is based on discrete, deterministic systems. It is believed that the research may be extended for both continuous and probabilistic systems. Although probabilistic systems are relevant to the validation question proposed for topic two, the extension to continuous systems is distinct. However, similar to the recommended path for topic two, it is recommended that a starting position be established through exploration of DEVS (e.g., chapters 9 and 21 of [73]), which may potentially be leveraged to address this research.

In regard to topic four, the methods used in this dissertation do not characterize different types of verification requirements. Rather, aspects of verification requirements are defined generically through verification requirement problem spaces that characterize the verification activity from the perspective of the transformations expected of the verification model and verification model morphic conditions that define the desired pedigree expected of the verification model relative to the system design. As discussed in [42], there are types of methods and models used for verification. To address the research question here, it is recommended to characterize each type of verification requirement and any limitations that may exist in leveraging the systems theoretic methods defined in this dissertation.

In regard to topic five, verification requirements are typically defined in the early phases when a system design does (or may) not exist. Verification models were defined based on the subset of system requirements for water-resistance. The third verification requirement problem space (VRPS3) for water-resistance was defined with explicit knowledge of the system design. The set of verification models defined based on the subset of system requirements was larger than the set of verification models defined based on the verification requirement problem space. In fact, the only verification models that were acceptable on the basis of the verification requirement problem space was the set of verification models that were based on the system design. This suggests that knowledge of the system design may change what is selected for the verification requirement problem space. Furthermore, the verification model morphic condition, which establish a desired representativeness of the verification model to the system design could be adjusted in specificity with knowledge of the system design and detail associated with which parameterization equivalence (e.g., input/output item being exchanged and/or interface) is desired for the specific verification activity.

In regard to topic six, the research in this dissertation has potential to be extended for verification planning, which is multi-faceted. In one facet, the much of the planning for the engineering of a system is dependent on the desired representativeness of the verification model to the system design. A verification model that has high representativeness (e.g., identity isomorphism) to a system design may not be available in early phases; therefore, a verification model with lower representativeness (e.g., any homomorphic image) to a system design may be leveraged. The specificity of the desired representatives of the verification model to the system design may be tuned based on selection of the verification model morphic conditions. It is recommended that this be combined with known verification (strategy) planning research (e.g., [33, 34]), which should address the research question.

In regard to topic seven, it is typical in current practice of SE to qualitatively define the fidelity of a verification model in early phases when verification requirements are defined. However, it is not typical to confirm the fidelity of early verification models; or verification model in general, as the research in this dissertation has shown. Because representativeness of verification models to a system design may be confirmed through the systems theoretic morphisms leveraged for this dissertation, the desired fidelity documented in early phases may be confirmed when a final product exists. In addressing this research question, the reconciliation between pedigree (verification model and system design) and fidelity (verification model and final product) may also be addressed. It is recommended to confirm the desired fidelity defined in early phases through leveraging systems theoretic morphisms similar to those defined in this dissertation.

In regard to topic eight, this dissertation assumed a static set of relationships between requirements, design, and verification; which was sufficient to address the research question. However, in practice the relationships between requirements, design, and verification are dynamic. For example, requirements are the basis for contracts, which may change based on the results of a verification activity that discovers conflicting requirements. Furthermore, as discussed for topic five, verification requirement may be better defined (or change) once knowledge of the system design exists. To address this research question, it is recommended to study the dynamic relationship between requirements, design, and verification through a set of morphic knowledge chains between verification frames characterized through the systems theoretic methods defined by this dissertation.

In regard to topic nine, a small set of system morphisms was selected for this dissertation. The foundational morphism leveraged is the homomorphism and a subset of types of homomorphisms. For example, an isomorphism is a homomorphism with a one-to-one mapping of equivalence. Other morphisms that exist that may extend the body of research of this dissertation. Other subsets of homomorphisms may be leveraged, for examples, an endomorphism is a homomorphism of a system produced by the system of the system itself and an automorphism is an isomorphism of a system relative to itself in which perspective, such as rotation, changes. Furthermore, as discussed previously, the use of homeomorphism, which is specific to topology, is a morphism that may prove to extend this dissertation research. Although a few examples morphisms beyond what was leveraged for this dissertation exist, more morphisms may exist that may contribute to extending this dissertation research, which is recommended for further exploration.

In regard to topic ten, the methods used to address the research question in this dissertation were notably manual. Simply stated, the software to fully implement this research does not exist. A path that was explored was the use of translation software between SysML state machine diagrams and T3SD, Moore-based mathematical structure such as implied in [78, 79]. However, the software was not completed in time for this dissertation. The MS4 Me software was selected due to it being a software implementation of the DEVS formalism. However, MS4 Me does not translate to the underlying mathematical structures, which were deemed necessary to prove the relationships for this dissertation research. As such, the T3SD-based tabular forms were selected, which was notably manual. Furthermore, within the MS4 Me software, the proof of morphisms required manual coding specific to the cases selected for this dissertation. The concepts of model checking (e.g., [80]) may provide some insights to automation of the methods in this dissertation. Model checking is used to characterize behavioral equivalence, which has been suggested to be complementary to the combined behavioral and structural equivalence characterized through Wymorian systems theory [81]. A note of caution with automation exists with the pizza example in this dissertation, which suggest that human oversight may be advisable to avoid automated selection of the counter-intuitive. This may, be resolved by placing morphic conditions on the equivalence between the system requirements and verification requirement problem spaces. However, it must also be noted that requirements (both system and verification) are contracts and a human (and machine) may choose select a pizza as a verification model for a flashlight system design. An aspect of automation that should also be considered is reuse, such as with the implication of Wymore's suggestion for the reuse of commercial-off-the-shelf (COTS) products [75] and the consistency of DEVS with object-oriented programming (OOP) (e.g., [82, 83]). The use of IoX versus inputs/outputs is also consistent with OOP, which suggests that the methods in this dissertation support reuse. Software implementation, and automation specifically, is believe to be necessary to notably expand the research; which will be explored in further detail as to next steps.

References

[1] P. Zimmerman, T. Gilbert, and F. Salvatore, "Digital engineering transformation across the Department of Defense," *The Journal of Defense Modeling and Simulation,* vol. 16, no. 4, pp. 325-338, 2019.

[2] INCOSE. (2007, May 28). *Model-Based Systems Engineering (MBSE) (glossary)*. Available: https://www.sebokwiki.org/wiki/Model-Based_Systems_Engineering_(MBSE)_(glossary)

[3] S. Friedenthal, A. Moore, and R. Steiner, 3rd, Ed. *A Practical Guide to SysML—The Systems Modeling Language*. Waltham, MA, USA: Morgan Kaufman, 2015.

[4] P. Wach, A. Salado, and A. Kulkarni, "A Systematic Literature Review on the Math of Model-Based Systems Engineering," *Systems Engineering,* submitted 2021.

[5] M. Bajaj, B. Cole, and D. Zwemer, "Architecture To Geometry - Integrating System Models With Mechanical Design," in *AIAA SPACE 2016*(AIAA SPACE Forum: American Institute of Aeronautics and Astronautics, 2016.

[6] B. P. Zeigler, S. Mittal, and M. K. Traore, "MBSE with/out Simulation: State of the Art and Way Forward," *Systems,* vol. 6, p. 40, 2018.

[7] K. P. Triantis and P. D. Collopy, "A comprehensive basis for systems engineering theory," in *2014 IEEE International Systems Conference Proceedings*, 2014, pp. 97-102: IEEE.

[8] P. D. Collopy, "Report on the science of systems engineering workshop," in *53rd AIAA aerospace sciences meeting*, 2015, p. 1865.

[9] P. D. Collopy, "Systems engineering theory: What needs to be done," in *2015 Annual IEEE Systems Conference (SysCon) Proceedings*, 2015, pp. 536-541.

[10] INCOSE. (June 9). *Future of Systems Engineering (FuSE)*. Available: https://www.incose.org/about-systems-engineering/fuse

[11] D. Rousseau and J. Calvo-Amodio, "Systems Principles, Systems Science, and the Future of Systems Engineering," *INSIGHT,* vol. 22, no. 1, pp. 13-15, 2019.

[12] D. Rousseau, "The Theoretical Foundation(s) for Systems Engineering? Response to Yearworth," *Systems Research and Behavioral Science,* vol. 37, no. 1, pp. 188-191, 2020.

[13] D. Rousseau, "A vision for advancing systems science as a foundation for the systems engineering and systems practice of the future," *Systems Research and Behavioral Science,* vol. 36, no. 5, pp. 621-634, 2019.

[14] O. Hammami and W. Edmonson, "THEFOSE - Theoretical Foundations of System Engineering: A first feedback," in *2015 IEEE International Symposium on Systems Engineering (ISSE)*, 2015, pp. 370-374.

[15] W. D. Schindel, "Identifying phenomenological foundations of systems engineering and systems science," *Systems Research and Behavioral Science,* vol. 36, no. 5, pp. 635-647, 2019/09/01 2019.

[16] N. S. F. (NSF). (October 2015, June 9). *Workshop: Investigation of the Theoretical Foundations in Systems Engineering*. Available: https://www.nsf.gov/awardsearch/showAward?AWD_ID=1548480

[17] N. S. F. (NSF). (2014, June 9). *Workshop: The Science of Systems Engineering*. Available: https://nsf.gov/awardsearch/showAward?AWD_ID=1447031

[18] INCOSE. (2014, November 12). *INCOSE System Egineering Vision 2025 July, 2014*. Available: https://www.incose.org/docs/default-source/aboutse/se-vision-2025.pdf?sfvrsn=4&sfvrsn=4

[19] L. von Bertalanffy, *General Systems Theory—Foundations, Development, Applications*. New York, NY, USA: George Braziller, Inc., 1969.

[20] M. Mesarovic and Y. Takahara, *General Systems Theory: Mathematical Foundations*. London, UK: Academic Press, 1975.

[21] M. Mesarovic and Y. Takahara, *Abstract Systems Theory*. New York, USA: Springer-Verlag, 1989.

[22] A. W. Wymore, *A Mathematical Theory of Systems Engineering - the Elements*. New York, NY, USA: John Wiley and Sons Inc., 1967.

[23] A. W. Wymore, *Model-Based Systems Engineering*. 2000 NW Corporate Blvd., Boca Raton, FL, USA 33431: CRC Press LLC, 1993.

[24] E. A. Bjorkman, S. Sarkani, and T. A. Mazzuchi, "Using model-based systems engineering as a framework for improving test and evaluation activities," *Systems Engineering,* vol. 16, no. 3, pp. 346-362, 2013/09/01 2013.

[25] A. M. Farid, "An Engineering Systems Introduction to Axiomatic Design," in *Axiomatic Design in Large Systems: Complex Products, Buildings and Manufacturing Systems*, A. M. Farid and N. P. Suh, Eds. Cham: Springer International Publishing, 2016, pp. 3-47.

[26] M. A. Mabrok, S. Elsayed, and M. J. Ryan, "Mathematical framework for recursive model-based system design," *Nonlinear Dynamics,* vol. 84, no. 1, pp. 223-236, 2016/04/01 2016.

[27] M. Mabrok and M. Ryan, "Category Theory as a Formal Mathematical Foundation for Model-Based Systems Engineering," *Appl. Math. Inf. Sci.,* vol. 11, no. 1, pp. 43-51, 2017.

[28] A. W. Wymore, "Systems Movement: Autobiographical Retrospectives," *International Journal of General Systems,* vol. 33, no. 6, 2004.

[29] INCOSE. (2022, Mar 16). *Systems Engineering Vision 2035*. Available: https://www.incose.org/about-systems-engineering/se-vision-2035

[30] INCOSE, *Systems Engineering Handbook*, Fourth ed. Wiley, 2015.

[31] NASA, *NASA Systems Engineering Handbook*. Washington DC, USA: National Aeornautics and Space Administration (NASA), 2016.

[32] USDoD, "Systems Engineering," in *Defense Acquisition Guidebook*: US Department of Defense, 2020.

[33] A. Salado and H. Kannan, "A mathematical model of verification strategies," *Systems Engineering,* vol. 21, no. 6, pp. 593-608, 2018/11/01 2018.

[34] A. Salado and H. Kannan, "Properties of the utility of verification," in *2018 IEEE International Systems Engineering Symposium (ISSE)*, 2018, pp. 1-8: IEEE.

[35] A. Engel, *Verification, validation, and testing of engineered systems*. John Wiley & Sons, 2010.

[36] A. Engel and M. Barad, "A methodology for modeling VVT risks and costs," *Systems engineering,* vol. 6, no. 3, pp. 135-151, 2003.

[37] A. U. Kulkarni, A. Salado, C. Wernz, and P. Xu, "Is verifying frequently an optimal strategy? A belief-based model of verification," in *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2020, vol. 83983, p. V009T09A061: American Society of Mechanical Engineers.

[38] A. Salado, "A systems-theoretic articulation of stakeholder needs and system requirements," *Systems Engineering,* 2021.

[39] A. Salado, R. Nilchiani, and D. Verma, "A contribution to the scientific foundations of systems engineering: Solution spaces and requirements," *Journal of Systems Science and Systems Engineering,* vol. 26, no. 5, pp. 549-589, 2017/10/01 2017.

[40] A. Salado and P. Wach, "Constructing True Model-Based Requirements in SysML," *Systems,* 28 March 2019 2019.

[41] INCOSE, "Guide for writing requirements," *The International Council of Systems Engineering,* 2012.

[42] W. J. Larson, D. Kirkpatrick, J. J. Sellers, D. Thomas, and D. Verma, *Applied Space Systems Engineering* (Space Technology Series). The McGraw-Hill Companies, Inc., 2009.

[43] R. Oosthuizen and L. Pretorius, "Analysis of INCOSE Systems Engineering journal and international symposium research topics," *Systems Engineering,* 2021.

[44] P. Wach, B. P. Zeigler, and A. Salado, "Conjoining Wymore's Systems Theoretic Framework and the DEVS Modeling Formalism: Toward Scientific Foundations for MBSE," *Applied Sciences,* vol. 11, no. 11, p. 4936, 2021.

[45] L. Delligatti, *SysML Distilled: A Brief Guide to the Systems Modeling Language*. Crawfordsville, Indiana, USA: Pearson Education, Inc, 2014.

[46] S. Gebreyohannes, W. Edmonson, J. Chenou, N. Neogi, and A. Esterline, "Formal requirement management for the Responsive and Formal Design process," in *2015 IEEE International Symposium on Systems Engineering (ISSE)*, 2015, pp. 364-369.

[47] S. Gebreyohannes, W. Edmonson, and A. Esterline, "Formalization of the responsive and formal design process using category theory," in *2018 Annual IEEE International Systems Conference (SysCon)*, 2018, pp. 1-8.

[48] S. Gebreyohannes, W. Edmonson, A. Esterline, A. Homaifar, and N. Kibret, "Fuzzy classification context for the responsive and formal design process," in *2017 Annual IEEE International Systems Conference (SysCon)*, 2017, pp. 1-8.

[49] N. Kibret, W. Edmonson, and S. Gebreyohannes, "Ontology-Driven Requirements Engineering in the Responsive and Formal Design Process," Cham, 2019, pp. 395-405: Springer International Publishing.

[50] N. Kibret, W. Edmonson, and S. Gebreyohannes, "Category theoretic based formalization of the verifiable design process," in *2019 IEEE International Systems Conference (SysCon)*, 2019, pp. 1-8: IEEE.

[51] A. W. Wymore, "2.5. 5 A System Theoretic Framework for V&V," in *INCOSE International Symposium*, 2002, vol. 12, no. 1, pp. 1223-1229: Wiley Online Library.

[52] A. Salado and P. Wach, "Automatic generation of contractual requirements from MBSE artifacts," Acquisition Research Program2019.

[53] P. Wach, P. Beling, and A. Salado, "Initial Systems Theoretic Metamodel of Verification Artifacts," presented at the CSER, Norwegian Univeristy of Science and Technology, Norway, 2022.

[54] P. Wach and A. Salado, "Model-Based Security Requirements for Cyber-Physical Systems in SysML," presented at the IEEE System Security Symposium, Washington DC, USA, 2020.

[55] P. Wach and A. Salado, "The Need for Semantic Extension of SysML to Model the Problem Space," presented at the Conference on Systems Engineering Research (CSER) 2020, Redondo Beach, CA, 2020.

[56] P. Wach and A. Salado, "True Model-Based Requirements (TMBR): Application to an Earth Observation Satellite," presented at the AIAA SciTech, Virtual, 2021.

[57] P. Wach and A. Salado, "Model-Based Requirements (TMBR) of a Satellite TTC Transponder," in *2021 IEEE Aerospace Conference*, 2021, pp. 1-12.

[58] B. P. Zeigler, H. Praehofer, and T. G. Kim, *Theory of Modeling and Simulation: Discrete Event & Iterative System Computational Foundations*. New York, USA: Academic Press, 2000.

[59] B. P. Zeigler, J. W. Marvin, and J. J. Cadigan, "Systems engineering and simulation: converging toward noble causes," in *2018 Winter Simulation Conference (WSC)*, 2018, pp. 3742-3752: IEEE.

[60] B. P. Zeigler and J. J. Nutaro, "Towards a framework for more robust validation and verification of simulation models for systems of systems," *The Journal of Defense Modeling and Simulation,* vol. 13, no. 1, pp. 3-16, 2016.

[61] J. Ring, "About Intelligent Enterprises: A Collection of Knowledge Claims," *INCOSE International Symposium,* vol. 17, no. 1, pp. 1964-2079, 2007.

[62] J. Ring, "2.6. 3 The Next Venue for Systems Engineering," in *INCOSE International Symposium*, 2001, vol. 11, no. 1, pp. 900-907: Wiley Online Library.

[63] M. M. White, J. A. Lacy, and E. A. O'Hair, "Refinement of the Requirements Definition (RD) Concept in System Development: Development of the RD Areas," in *INCOSE International Symposium*, 1996, vol. 6, no. 1, pp. 762-770: Wiley Online Library.

[64] T. L. Ferris, "9.1. 3 development of a framework of research topics in systems engineering," in *INCOSE International Symposium*, 2009, vol. 19, no. 1, pp. 1378-1390: Wiley Online Library.

[65] R. A. Martin, "Enabling Intelligence with Ontology," *INSIGHT,* vol. 6, no. 2, pp. 12-15, 2004.

[66] J. Carl and J. Hofmeister, "7.6. 2 OBJECT-ORIENTED AND STRUCTURED ANALYSES ARE HOMEOMORPHIC," in *INCOSE International Symposium*, 2004, vol. 14, no. 1, pp. 1581-1590: Wiley Online Library.

[67] Z. B. Miled and M. O. French, "Towards A Reasoning Framework for Digital Clones Using the Digital Thread," in *55th AIAA Aerospace Sciences Meeting*, 2017.

[68] T. Cody, "A Systems Theory of Transfer Learning with Application," PhD, Systems Engineering - School of Engineering and Applied Science, University of Virginia, 2021.

[69] G. Bakirtzis, "Compositional cyber-physical systems theory," *arXiv preprint arXiv:2109.04858,* 2021.

[70] G. Bakirtzis, E. Subrahmanian, and C. H. Fleming, "Compositional Thinking in Cyberphysical Systems Theory," *Computer,* vol. 54, no. 12, pp. 50-59, 2021.

[71] S. Takahashi, "Systems Modeling," in *Handbook of Systems Sciences*, G. S. Metcalf, K. Kijima, and H. Deguchi, Eds. Singapore: Springer Singapore, 2021, pp. 267-290.

[72] P. Wach, P. Beling, and A. Salado, "Formalizing the Representativeness of Verification Models using Morphisms," presented at the INCOSE-IS, Detroit, MI, USA, 2022.

[73] B. P. Zeigler, A. Muzy, and E. Kofman, *Theory of Modeling and Simulation: Discrete Event & Interative System Computational Foundations*. London Wall, London, UK: Elsevier Inc, 2019.

[74] E. F. Moore, "Gedanken-experiments on Sequential Machines," in *Automata Studies, Annals of Mathematical Studies*, vol. 34Princeton, N.J.: Princeton University Press, 1956, pp. 129-153.

[75] A. W. Wymore and A. T. Bahill, "When can we safely reuse systems, upgrade systems, or use COTS components?," *Systems Engineering,* vol. 3, no. 2, pp. 82-95, 2000.

[76] RTsync. (Feb 13). *MS4 Systems*. Available: http://www.ms4systems.com/pages/main.php

[77] T. I. Ören, "Gest: general system theory implementor (a combined digital simulation language)," 1971.

[78] P. Wach and A. Salado, "A Research Plan to Discover Patterns of Unknown Vulnerabilities Associated with Adopting SysML," Cham, 2019, pp. 279-289: Springer International Publishing.

[79] P. Wach and A. Salado, "Can Wymore's Mathematical Framework Underpin SysML? An Initial Investigation of State Machines," *Procedia Computer Science,* vol. 153, pp. 242-249, 2019/01/01 2019.

[80] E. M. Clarke, T. A. Henzinger, H. Veith, and R. Bloem, *Handbook of model checking*. Springer, 2018.

[81] B. P. Zeigler, J. J. Nutaro, and C. Seo, "Combining DEVS and model-checking: concepts and tools for integrating simulation and analysis," *International Journal of Simulation and Process Modelling,* vol. 12, no. 1, pp. 2-15, 2017.

[82] M. E. A. Hamri, "An Object-Oriented Framework for Designing Reusable and Maintainable DEVS Models using Design Patterns," *arXiv preprint arXiv:2008.06587,* 2020.

[83] B. P. Zeigler and H. S. Sarjoughian, "Introduction to devs modeling and simulation with java: Developing component-based simulation models," *Technical Document, University of Arizona,* 2003.

[84] A. W. Wymore, "SYNERGY: The design of a systems engineering system, I," Berlin, Heidelberg, 1996, pp. 34-45: Springer Berlin Heidelberg.

[85] A. W. Wymore. (1998, June 10). *Subsystem Optimization Implies System Suboptimization: Not!* Available: http://sysengr.engr.arizona.edu/wymore/optimal.html

[86] A. W. Wymore, *Systems engineering methodology for interdisciplinary teams*. Wiley-Interscience, 1976.

[87] A. W. Wymore, "T3SD as a Modeling methodology," in *Adequate Modeling of Systems*: Springer, 1983, pp. 185-199.

[88] A. W. Wymore, "2 SYSTEM THEORETIC PORTENTS OF PREDISPOSITION TO SYSTEM FAILURE," in *INCOSE International Symposium*, 1999, vol. 9, no. 1, pp. 232-240: Wiley Online Library.

[89] W. Wymore, C. Onstad, and L. Lane, "AGUAS: Design of an Agricultural Water Quality System," in *INCOSE International Symposium*, 1994, vol. 4, no. 1, pp. 779-786: Wiley Online Library.

[90] B. P. Zeigler, *Multifacetted Modelling and Discrete Event Simulation*. Orlando, FL, USA: Academic Press Inc (London) Ltd, 1984.

[91] B. P. Zeigler, "Closure under coupling: concept, proofs, DEVS recent examples (wip)," presented at the Proceedings of the 4th ACM International Conference of Computing for Engineering and Sciences, Kuala Lumpur, Malaysia, 2018. Available: https://doi.org/10.1145/3213187.3213194

[92] B. P. Zeigler, "The role of approximate morphisms in multiresolution modeling: Can we relax the strict lumpability requirements?," *The Journal of Defense Modeling and Simulation,* vol. 15, no. 4, pp. 495-498, 2018.

[93] B. P. Zeigler and H. Sarjoughian, *Guide to Modeling and Simulation of Systems of Systems*, Second ed. Cham, Switzerland: Springer International Publishing AG, 2017.

[94] L. Zhang, B. P. Zeigler, and Y. Laili, *Model Engineering for Simulation*. Cambridge, MA, USA: Elsevier, 2019.

Appendix A

A.1 Glossary of acronyms

Acronym list and descriptions are provided in Table 122 for general terms, Table 123 for some DEVS specific terms, and Table 124 for some T3SD specific terms.

Table 122: General terms

Acronym	Full Term and/or description
B	Is a SM at Level 2 (captures SCR and Z@)
DEVS	Discrete event system specification
F	IoX to IF mapping function
IF	Interface (through which IoX are transferred)
IoX	Input/output item of exchange
L0	Level 0 (is a PSF)
L1	Level 1 (SM specified as Z or Z@)
L2	L2 (SM specified as B, SCR)
MBSE	Model-based systems engineering
MS4 Me	Modeling for systems modeling environment (DEVS-based software)
P	Set of IF
PSF	Problem space of functions (mathematical basis for SR and VRPS, Level 0)
S	Set of states
SCR	Set of system coupling recipes (coupling of components at L2)
SD	System design (is an instantiated a SM)
SE	System engineering
SM	System model (underlying mathematical structure for SD and VM)
SR	System requirements (is an instantiated a PSF)
T3SD	Tricotyledon theory of system design (Wymore's theory of MBSE)
VF	Vector of systems (components) to be coupled in SCR
VM	Verification model (is an instantiated a SM)
VMMC	Verification model morphic conditions (desired pedigree between SD-VM)
VR	Verification requirement (combo of VRPS and VMMC)
VRPS	Verification requirement problem space (is an instantiated a PSF)
VZ	Vector of IoX and IF mapping between components to be coupled in SCR
X	Set of input IoX
XY	Set of functions that transform input IoX to output IoX
Y	Set of output IoX
Z	Is a SM at Level 1
Z@	Is the resultant SM from SCR at Level 1

Table 123: Other DEVS specific terms

Acronym	Full Term and/or description

EF	Experimental frame
IO Observation	Input/output observation frame
IORO	Input/output relation observation
IOFO	Input/output function
IO System	Input/output system
Network of systems	Coupled IO System components

Table 124: Other T3SD specific terms

Acronym	Full Term and/or description
BSD	Buildable system design
FSD	Functional system design
ISD	Implementable system design

A.2 Theoretical background of Wymorian Systems Theory

In this section, background is provided for the theoretical context that was leveraged. Specifically, this section provides an overview of T3SD and DEVS.

A.2.1 Theoretical background on T3SD

The main source used for this section is Wymore's book titled Model-Based Systems Engineering [23], which contains the mathematically rigorous prescription of T3SD. Other sources used to construct this section include [51, 75, 84-89]. Further summary context of T3SD is published in [44].

The high-level metamodel of T3SD is shown in Figure 22. Aspects not shown for conciseness include those related to trades analysis. For a more detailed metamodel, please review [44].

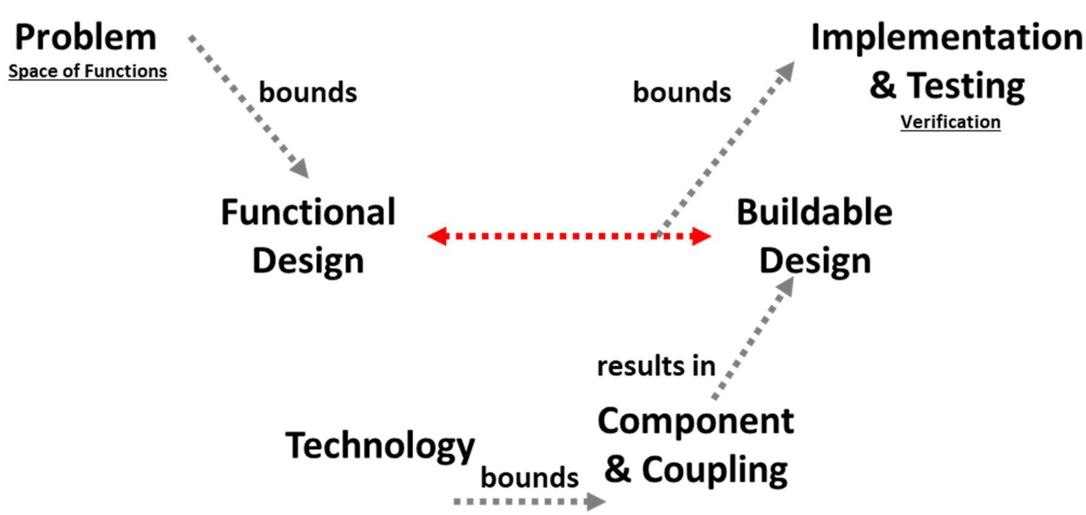

Figure 22: High-level metamodel of T3SD [72]

T3SD earned its name from the cotyledons that form three spaces of "system designs": the functional space shown as problem space of functions in Figure 1, the buildable space shown as Technology in Figure 1, and implementable space shown as Implementation & Testing (and verification) in Figure 1. Note, a system design in the context of T3SD is a model that exists initially prior to the existence of a final product.

The problem space of functions is characterized by desired input/output transformations. This space defines a boundary of functional system designs that can be specified as acceptable versus those that are not acceptable. A functional system design is considered to be a minimum system model of the system design [75] and is represented as a Moore-based state machine [74].

The space of buildable system designs provides a boundary of acceptable (e.g., available) technology such as components and interfaces. Each component model is represented as a Moore-based state machine [74]. The resultant of coupling of the components is a single Moore state machine. The resultant buildable system design is generally expected to be more elaborate (have more detailed structure) than the functional system design.

The space of implementable system designs is formed from a mathematical characterization of equivalence between the more abstract functional system design and the more elaborate buildable system design. The mathematical characterization of equivalence, shown as the red arrows in the middle of Figure 2, is referred to as a morphism; specifically, homomorphism is the general morphism used in T3SD. The morphism is a means to enforce adherence to a design that adheres to the problem space of functions. The implementable system design is what is tested (i.e., verified), which is conducted based on a subset of input/output transformations defined as part of the problem space of functions. The final product is product is produced on the basis of the implementable system design.

The problem space of functions shown in Figure 2 is formally referred to as the *input/output requirement* (IOR) within T3SD, which is defined in the following tuple [23]:

$$IOR = (OLR, IR, ITR, OR, OTR, ER), \tag{9}$$

where *OLR* is the *operational life requirement*, *IR* is the *set of inputs*, *ITR* defines the *input trajectories*, *OR* is the *set of outputs*, O*TR* defines the *output trajectories*, and *ER* is the *eligibility function* which maps eligible sets of output trajectories to be produced from sets of input trajectories.

Referred to as the "functional design" in Figure 2, the *functional system design* (*FSD*) in bound by the IOR. The FSD is defined as a tuple [23]:

$$FSD = (Z, DS_Z, TS_Z), \tag{10}$$

where Z is the *minimum model of the system*, DS_Z is the *initial state*, and TS_Z is the *discrete timescale* of the system. The minimum system model, Z, is a discrete system model based on the Moore state machine and is defined as a quintuple [23]:

$$Z = (S_Z, I_Z, O_Z, N_Z, R_Z), \tag{11}$$

where Z is the name (i.e., identifier) of the system, S_Z is the set of its states, I_Z is the set of its inputs, O_Z is the set of its outputs, N_Z is its next state function, and R_Z is its readout function that specifies the outputs for each state.

Referred to as the "buildable design" in Figure 2, the *buildable system design* (*BSD*) is formally defined as a tuple [23]:

$$BSD = (Z@, SCR), \tag{12}$$

where *SCR* is the system coupling recipe used to define connectivity of components, subsystems, and systems; and *Z@* is the resultant system from the coupling. Z@ has the same Moore-based state machine as in Equation 3; however, the @ symbol is used to indicate that the system model is a resultant from the coupling of components. Note, each component is also based on Equation 3. The SCR is formally defined as a tuple [23]:

$$SCR = (V_{SCR}, C_{SCR}), \tag{13}$$

where V_{SCR} is the vector systems to be coupled and C_{SCR} is the system connectivity between outputs and inputs. The SCR is described as "the mathematical theory of system coupling: how systems can be put together by input/output relationships to create hierarchical models of more complex systems" [23].

Referred to as "implementation" in Figure 2, the *implementable system design* (*ISD*) is defined as a tuple [44]:

$$ISD = (FSD, BSD, IA), \tag{14}$$

where FSD is the functional system design, BSD is the buildable system design and *IA* is the *implementation artifacts* that captures the homomorphism between the FSD and BSD. The IA is defined as a tuple [44]:

$$IA = (Z_S, H_S, H_I, H_O), \tag{15}$$

where Z_S are the components, subcomponents, and modes of the real system; H_S is a homomorphic mapping between states of the FSD and BSD; H_I is a homomorphic mapping between inputs of the FSD and BSD; and H_O is a homomorphic mapping between outputs of the FSD and BSD.

Homomorphism, shown as the red arrows in the middle of Figure 2, in T3SD is formally defined as follows [23]: One system (e.g., FSD) is a homomorphic image of another system (e.g., BSD) with respect to a set of inputs $I_2 \subseteq IZ_2$, a set of outputs $O_2 \subseteq OZ_2$, and a set of states $Q_2 \subseteq SZ_2$ if and only if:

i) there exists a surjection $hi: I_2 \to I_1$, where $I_1 \subseteq IZ_1$,
ii) there exists a surjection $ho: O_2 \to O_1$, where $O_1 \subseteq OZ_1$,
iii) there exists a surjection $hq: Q_2 \to Q_1$, where $Q_1 \subseteq SZ_1$,
iv) $hq\big(NZ_2(x, i)\big) = NZ_1\big(hq(x), hi(i)\big), \forall x \in Q_2, i \in I_2$,

v) $ho\big(RZ_2(x)\big) = RZ_1\big(hs(x)\big), \forall x \in Q_2.$

A.2.2 Theoretical background on DEVS

The description of DEVS is largely based on [73], with supporting summary of DEVS provided in [44]. Other sources leveraged or recommended for further reading on DEVS include [6, 59, 60, 81, 90-94].

A metamodel of the DEVS hierarchy of system specification is provided in below Figure 23. The hierarchy is typically defined starting with the Input/Output (IO) [Observation] Frame (IO Frame) as level 0, IO Relation Observation (IORO) as level 1, IO Function Observation (IOFO) as level 2, IO System as level 3, and the Network of Systems as level 4. At level 0, the IO Frame has the least amount of system structure specified. At level 4, the Network of Systems has the most amount of system structure specified. Note, the IO Frame, IORO, and IOFO are independent of internal structure, with the exception that IOFO captures the notion of an initial state that is, however, only initial in the context of a single function of the system. The IO System create a single system function that is closed under concatenation and represents the internal global behavior of the system that is specified. The Network of Systems have the most internal structure specified and are composed of independent components (systems) that are IO Systems coupled together. The concepts of DEVS suggest that for every one IO Frame there are many (possibly infinite) system structures that can be defined down to the Network of Systems specification; and vice versa, for every Network of Systems that is specified there is only one IO Frame that is maps to. At each level of system specification within the hierarchy there exist a system morphism. A system morphism is defined as a mathematical characterization of equivalence between a pair [73].

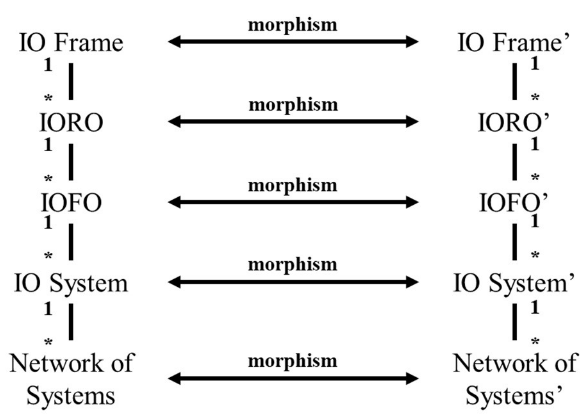

Figure 23: Metamodel of the DEVS hierarchy of system specification

From the overview of DEVS from the perspective of the metamodel of the hierarchy of system specification, we now provide the mathematical description of each system specification and the corresponding system morphism, which were adopted from [73] (with permission).

$$IO = (T, X, Y) \quad (16)$$

Where *IO* is the *Input/Output (I/O) Observation Frame* (chapter 5.3 and 15.1 of [73]), T is the *time base*, X is the *input values set*, and Y is the *output values set*.

We relate two system IO = (T, X, Y) and IO' = (T', X', Y') at the I/O Frame level by defining functions to relate the input and outputs interfaces. Let g : (X', T')→(X, T) be a function to define a segment over X given a segment over X' and k : (Y, T)→$_{onto}$ (Y', T') be a function to define an output segment over output set over Y' of the little system given an output segment over Y of the big system S.

$$IORO = (T, X, \Omega, Y, R) \quad (17)$$

Where IORO is the *I/O Relation* (chapter 5.4 and 15.2 of [73]), T is the *time base*, X is the *input values set*, Ω is the *set of allowable input segments*, Y is the *output values set*, and R is the *I/O relation* with constraints that (a) $\Omega \subseteq (X, T)$ and (b) $R \subseteq \Omega \times (X, T)$ where $(\omega, \rho) \in R \Rightarrow dom(\omega) = dom(\rho)$.

Let S (more iteratively elaborate) and S' (more iteratively abstract) be represented by I/O relation observation (T, X, Ω, Y, R) and (T', X', Ω', Y', R'). Mapping from S' to S such that:

1. g : Ω' → Ω

2. k : (Y, T)→onto (Y', T')

3. For every pair (ω', ρ') ∈ R', there exists (ω, ρ) ∈ R such that ω = g(ω') and k(ρ) = ρ'

Mapping from S to S' such that:

1. g : Ω →onto Ω'
2. k : (Y, T)→onto (Y', T')
3. for every pair (ω, ρ) ∈ R, there exists (ω', ρ') ∈ R' such that ω' = g(ω) and ρ' = k(ρ)

$$IOFO = (T, X, \Omega, Y, R) \quad (18)$$

Where IOFO is the *I/O Function* (chapter 5.5 and 15.3 of [73]), T is the *time base*, X is the *input values set*, Ω is the *set of allowable input segments*, Y is the *output values set*, and F is *the set of I/O functions* with constraints that (a) $\Omega \subseteq (X, T)$, (b) $f \in F \rightarrow f \subseteq \Omega \times (X, T)$ is a function and (c) if where $\rho = f(\omega)$, then $dom(\omega) = dom(\rho)$.

An I/O function morphism from an *IOFO = (T, X, Ω, Y, F)* to an *IOFO' = (T', X', Ω', Y', F')* is a pair *(g, k)* where

1. *g* : *Ω' →Ω*
2. *k* : *(Y, T)→onto (Y', T')*
3. For each *f' ∈ F'* there is an *f* ∈ *F* such that *f' = k ∘ f ∘ g*, i.e., for all *ω' ∈ Ω '*, *f'(ω') = k(f (g(ω')))*.

$$S = (T, X, \Omega, Y, Q, \Delta, \Lambda) \quad (19)$$

Where S is an *I/O System* (chapter 5.6 and 15.4 of [73]), T is the *time base*, X is the *input values set*, Ω is the *set of allowable input segments*, Y is the *output values set*, Q is *the set of states*, $\Delta : Q \times \Omega \rightarrow Q$ is the *global state transition function*, $\Lambda : \Omega \times X \rightarrow Y$ (or $\Lambda : Q \rightarrow Y$) is the *output function* with constraints of *closure property* of Ω being closed under concatenation as well as under left segmentation and *composition (or semigroup) property* in that for every pair of contiguous input segments $\omega, \omega' \in \Omega$ $\Delta(q,\omega) = \Delta((\Delta(q,\omega),\omega')$ with $q \in Q$.

Let S (more iteratively elaborate) and S' (more iteratively abstract) be represented by $(T, X, \Omega, Y, Q, \Delta, \Lambda)$ and $(T', X', \Omega', Y', Q', \Delta', \Lambda')$ where the system morphism is a triple (g, h, k) such that

1. g: Ω' → Ω
2. h: $\overline{Q}$ →onto Q', where $\overline{Q} \subseteq Q$
3. k: Y →onto Y' and for all q ∈ Q, ω' ∈ Ω'
4. h(Δ(q, g(ω'))) = Δ'(h(q),ω') transition function preservation
5. k(Λ(q)) = Λ'(h(q)) output function preservation

$$N = (T, X_N, Y_N, D, \{M_d | d \in D\}, \{I_d | d \in D \cup \{N\}\}, \{Z_d | d \in D \cup \{N\}\}) \quad (20)$$

Where N is a *Coupled System (Network of Systems)* (chapter 5.8 and 15.8 of [73]), X_N is the *set of external input of the network*, Y_N is the *set of external outputs of the network*, D is the *set of component references* with $d \in D$, M_d is an *I/O System*, $I_d \subseteq D \cup \{N\}$ is the *set of influencers* of d, and $Z_d : \times_{i \in I_d} YX_i \rightarrow XY_d$ is the *interface map* for d with

$$YX_i = \begin{cases} X_i \; if \; i = N \\ Y_i \; if \; i \neq N \end{cases}$$

$$XY_d = \begin{cases} Y_d \; if \; i = N \\ X_d \; if \; i \neq N \end{cases}$$

Let N (more iteratively elaborate) and N' (more iteratively abstract) be represented by $(T, X_N, Y_N, D, \{M_d\}, \{I_d\}, \{Z_d\})$ and $(T', X'_{N'}, Y'_{N'}, D', \{M'_{d'}\}, \{I'_{d'}\}, \{Z'_{d'}\})$

We define a *network of systems morphism* from *N* onto *N'* as a structure $\langle coord, \{k_{d'}\}, \{g_{d'}\}, \{h_{d'}\} \rangle$ such that $\{k_{d'}\}$, $\{g_{d'}\}$ and $\{h_{d'}\}$ satisfy the coupling preservations, state transition preservation and input/output preservation conditions. Where *coord : D→onto D'* be a mapping from the set of components *D* of *N* onto the set of components D' of N'; $h_{d'}$ is a mapping of states; $k_{d'}$ is a mapping of outputs; and $g_{d'}$ is a mapping of inputs.

A.3 Example DEVS-based MS4 Me Validation Code

A.3.1 ZA MS4 Me Code

```
accepts input on IoXA1!
accepts input on IoXA2!
generates output on IoXA4!
generates output on IoXA3!
```

```
to start passivate in SA1!
when in SA1 and receive IoXA1 go to SA1!

external event for SA1 with IoXA1
<%//Add your own code
Serializable variable = messageList.get(0).getData();%>!
when in SA1 and receive IoXA2 go to trans12!

external event for SA1 with IoXA2
<%//Add your own code
Serializable variable = messageList.get(0).getData();%>!
hold in trans12 for time 0!
after trans12 output IoXA4!
from trans12 go to SA2!

output event for trans12
<%//Add your own code
output.add(outIoXA4,null);%>!

internal event for trans12
<%//place your own code for internal event here.%>!
passivate in SA2!
when in SA2 and receive IoXA2 go to SA2!

external event for SA2 with IoXA2
<%//Add your own code
Serializable variable = messageList.get(0).getData();%>!
when in SA2 and receive IoXA1 go to trans21!

external event for SA2 with IoXA1
<%//Add your own code
Serializable variable = messageList.get(0).getData();%>!
hold in trans21 for time 0!
after trans21 output IoXA3!
from trans21 go to SA1!

output event for trans21
<%//Add your own code
output.add(outIoXA3,null);%>!

internal event for trans21
<%//place your own code for internal event here.%>!
```

A.3.2 ZB MS4 Me Code

```
accepts input on IoXB2!
accepts input on IoXB1!
accepts input on IoXB3!
accepts input on IoXB4!
generates output on IoXB6!
generates output on IoXB5!
generates output on IoXB7!
```

```
to start passivate in SB1!
when in SB1 and receive IoXB2 go to trans12!

external event for SB1 with IoXB2
<%//Add your own code
Serializable variable = messageList.get(0).getData();
%>!
when in SB1 and receive IoXB1 go to SB1!

external event for SB1 with IoXB1
<%//Add your own code
Serializable variable = messageList.get(0).getData();
%>!
when in SB1 and receive IoXB3 go to SB1!

external event for SB1 with IoXB3
<%//Add your own code
Serializable variable = messageList.get(0).getData();
%>!
when in SB1 and receive IoXB4 go to SB1!

external event for SB1 with IoXB4
<%//Add your own code
Serializable variable = messageList.get(0).getData();
%>!
hold in trans12 for time 0!
after trans12 output IoXB6!
from trans12 go to SB2!

output event for trans12
<%//Add your own code
output.add(outIoXB6,null);
%>!

internal event for trans12
<%//place your own code for internal event here.
%>!
passivate in SB2!
when in SB2 and receive IoXB1 go to trans21!

external event for SB2 with IoXB1
<%//Add your own code
Serializable variable = messageList.get(0).getData();
%>!
when in SB2 and receive IoXB3 go to trans23!

external event for SB2 with IoXB3
<%//Add your own code
Serializable variable = messageList.get(0).getData();
%>!
when in SB2 and receive IoXB2 go to SB2!

external event for SB2 with IoXB2
<%//Add your own code
```

```
Serializable variable = messageList.get(0).getData();
%>!
when in SB2 and receive IoXB4 go to SB2!

external event for SB2 with IoXB4
<%//Add your own code
Serializable variable = messageList.get(0).getData();
%>!
hold in trans21 for time 0!
after trans21 output IoXB5!
from trans21 go to SB1!

output event for trans21
<%//Add your own code
output.add(outIoXB5,null);
%>!

internal event for trans21
<%//place your own code for internal event here.
%>!
hold in trans23 for time 0!
after trans23 output IoXB7!
from trans23 go to SB3!

output event for trans23
<%//Add your own code
output.add(outIoXB7,null);
%>!

internal event for trans23
<%//place your own code for internal event here.
%>!
passivate in SB3!
when in SB3 and receive IoXB4 go to trans32!

external event for SB3 with IoXB4
<%//Add your own code
Serializable variable = messageList.get(0).getData();
%>!
when in SB3 and receive IoXB1 go to SB3!

external event for SB3 with IoXB1
<%//Add your own code
Serializable variable = messageList.get(0).getData();
%>!
when in SB3 and receive IoXB2 go to SB3!

external event for SB3 with IoXB2
<%//Add your own code
Serializable variable = messageList.get(0).getData();
%>!
when in SB3 and receive IoXB3 go to SB3!

external event for SB3 with IoXB3
<%//Add your own code
```

```
Serializable variable = messageList.get(0).getData();
%>!
hold in trans32 for time 0!
after trans32 output IoXB6!
from trans32 go to SB2!

output event for trans32
<%//Add your own code
output.add(outIoXB6,null);
%>!

internal event for trans32
<%//place your own code for internal event here.
%>!
```

A.3.3 ZA Experimental Frame MS4 Me Code

A.3.3.1 Generator

```
generates output on IoXA1!
generates output on IoXA2!


to start hold in SendX for time 1!
after SendX output IoXA2!
from SendX go to SendY!

output event for SendX
<%//Add your own code
output.add(outIoXA2,null);

%>!

internal event for SendX
<%//place your own code for internal event here.
%>!
hold in SendY for time 1!
after SendY output IoXA1!
from SendY go to passive!

output event for SendY
<%//Add your own code
output.add(outIoXA1,null);

%>!

internal event for SendY
<%//place your own code for internal event here.
%>!
passivate in passive!
```

A.3.3.2 Experimental frame coupling

```
From the GenZAtoZAsys perspective, GenZAtoZA is made of  genA and ZA!

From the GenZAtoZAsys perspective, genA sends IoXA1 to ZA!
```

```
From the GenZAtoZAsys perspective, genA sends IoXA2 to ZA!

From the GenZAtoZAsys perspective, ZA sends IoXA3 to GenZAtoZA!
From the GenZAtoZAsys perspective, ZA sends IoXA4 to GenZAtoZA!
```

A.3.4 Homomorphism between ZA and ZB

```
// For homomorphism proof between ZA and ZB


package Models.java;



import java.util.Hashtable;


import com.ms4systems.devs.analytics.Function;
import com.ms4systems.devs.core.message.MessageBag;
import com.ms4systems.devs.core.message.impl.MessageBagImpl;
import com.ms4systems.devs.core.simulation.Simulation;
import com.ms4systems.devs.core.simulation.impl.SimulationImpl;
import com.ms4systems.devs.helpers.impl.SimulationOptionsImpl;
import com.ms4systems.devs.simviewer.standalone.SimViewer;

public class HomZAZB1 {



	public static void main(String[] args) {
		Hashtable h = new Hashtable();
		h.put("SB1","SA1");
		h.put("SB2","SA2");
		h.put("SB3","SA2");
```

```
SimulationOptionsImpl options = new SimulationOptionsImpl(args, true);

// Uncomment the following line to disable SimViewer for this model
//
options.setDisableViewer(true);

// Uncomment the following line to disable plotting for this model
// options.setDisablePlotting(true);

// Uncomment the following line to disable logging for this model
// options.setDisableLogging(true);
ZA ZA = new ZA();
ZB ZB = new ZB();
ZA.options = options;
ZB.options = options;
if (options.isDisableViewer()) { // Command line output only
        Simulation simA = new SimulationImpl("ZA Simulation", ZA,
options);
        Simulation simB = new SimulationImpl("ZB Simulation", ZB,
options);
        simA.startSimulation(0); // starts in initial state and time equals zero
        simB.startSimulation(0); // starts in initial state and time equals zero

        int i = 0; // starts in initial state and time equals zero
                MessageBag input = new MessageBagImpl();
                input.add(ZA.inIoXA2, null);
                simA.injectInput(i, input);
                simA.simulateIterations(1);
```

```
String aState = ZA.getPhase();
input = new MessageBagImpl();
input.add(ZB.inIoXB2, null);
simB.injectInput(i, input);
simB.simulateIterations(1);
String bState = ZB.getPhase();
String hZB = h.get(bState).toString();
System.out.println("Equal "+h.get(bState).equals(aState));

double Time = simB.getCurrentSimulationTime();




input = new MessageBagImpl();
input.add(ZB.inIoXB3, null);
simB.injectInput(i, input);
simB.simulateIterations(1);
bState = ZB.getPhase();
System.out.println("Equal "+h.get(bState).equals(aState));

Time = simB.getCurrentSimulationTime();

input = new MessageBagImpl();
input.add(ZB.inIoXB4, null);
simB.injectInput(i, input);
simB.simulateIterations(1);
bState = ZB.getPhase();
System.out.println("Equal "+h.get(bState).equals(aState));
```

```
                        input = new MessageBagImpl();
                        input.add(ZA.inIoXA1, null);
                        simA.injectInput(i, input);
                        simA.simulateIterations(1);
                        aState = ZA.getPhase();
                        input.add(ZB.inIoXB1, null);
                        simB.injectInput(i, input);
                        simB.simulateIterations(1);
                        bState = ZB.getPhase();
                        System.out.println("Equal "+h.get(bState).equals(aState));

                        aState = ZA.getPhase();
                        input = new MessageBagImpl();
                        input.add(ZA.inIoXA2, null);
                        simA.injectInput(i, input);
                        simA.simulateIterations(1);
                        aState = ZA.getPhase();
                        input.add(ZB.inIoXB1, null);
                        simB.injectInput(i, input);
                        simB.simulateIterations(1);
                        bState = ZB.getPhase();
                        System.out.println("Equal "+h.get(bState).equals(aState));
                }
        }

}
```

A.4 Mathematical definitions of the problem space of functions

A.4.1 Problem space of functions 1

Table 125 defines the mathematical structure of the PSF, Figure 24 provides a block diagram representation of IoX-IF mapping for the PSF, and Figure 25 provides a sequence diagram of desired transformation of the PSF.

Table 125: Tabular mathematical specification of a problem space of functions 1 (PSF_S1)

PSF_S1	(X_S1, Y_S1, XY_S1, F_S1, P_S1)
X_S1	{IoX_S1, IoX_S2, IoX_S5}
Y_S1	{IoX_S3, IoX_S4, IoX_S5}
XY_S1	{XY-S1, XY-S2, XY-S3}; where, XY-S1 = (IoX_S1, IoX_S3), XY-S2 = (IoX_S2, IoX_S4), and XY-S3 = (IoX_S5, IoX_S5)
F_S1	{IF-S1, IF-S2, IF-S3}
P_S1	{(IoX_S1, IF-S1), (IoX_S2, IF-S1), (IoX_S3, IF-S2), (IoX_S4, IF-S2), (IoX_S5, IF-S3)}

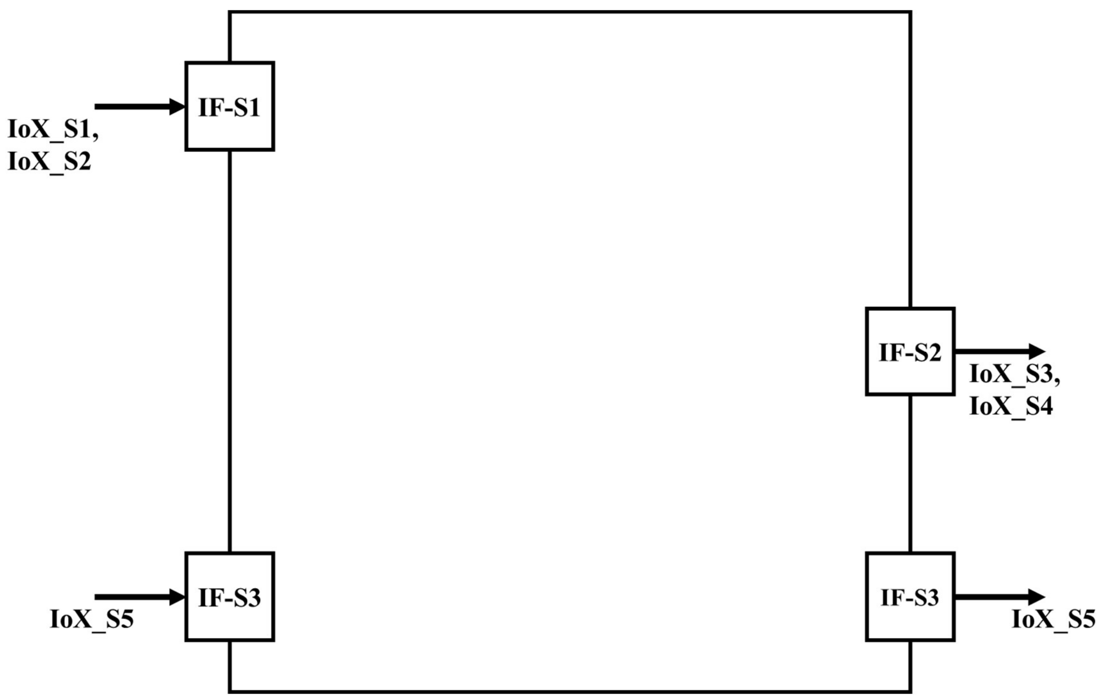

Figure 24: Block diagram description of the problem space of functions 1

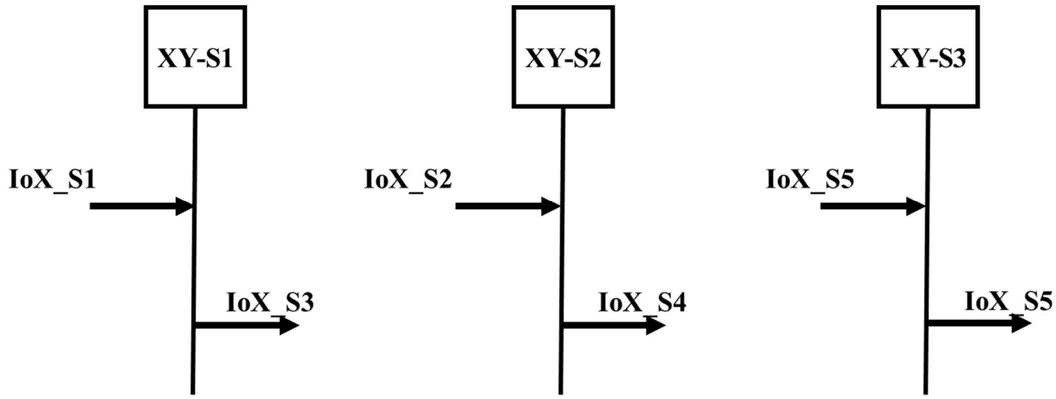

Figure 25: Sequence diagram description of the problem space of functions 1

A.4.2 Problem space of functions 2

Table 126 defines the mathematical structure of the PSF, Figure 26 provides a block diagram representation of IoX-IF mapping for the PSF, and Figure 27 provides a sequence diagram of desired transformation of the PSF.

Table 126: Tabular mathematical specification of a problem space of functions 1 (PSF_S2)

PSF_S2	(X_S2, Y_S2, XY_S2, F_S2, P_S2)
X_S2	{IoX_S1, IoX_S2}
Y_S2	{IoX_S3, IoX_S4}
XY_S2	{XY-S1, XY-S2}; where, XY-S1 = (IoX_S1, IoX_S3) and XY-S2 = (IoX_S2, IoX_S4)
F_S2	{IF-S1, IF-S2}
P_S2	{(IoX_S1, IF-S1), (IoX_S2, IF-S1), (IoX_S3, IF-S2), (IoX_S4, IF-S2)}

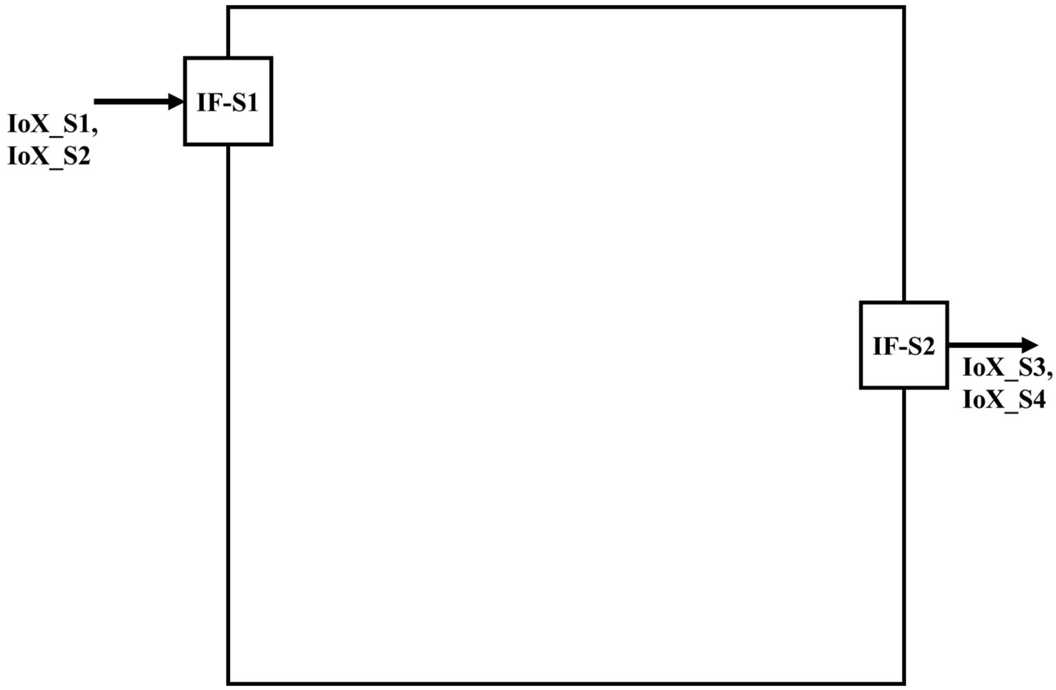

Figure 26: Block diagram description of the problem space of functions 2

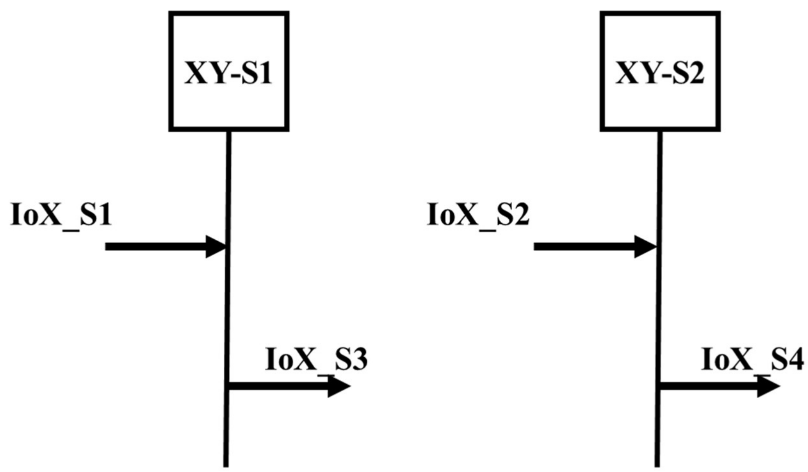

Figure 27: Sequence diagram description of the problem space of functions 2

A.4.3 Problem space of functions 3

Table 127 defines the mathematical structure of the PSF, Figure 28 provides a block diagram representation of IoX-IF mapping for the PSF, and Figure 29 provides a sequence diagram of desired transformation of the PSF.

Table 127: Tabular mathematical specification of a problem space of functions 1 (PSF_S3)

PSF_S3	(X_S3, Y_S3, XY_S3, F_S3, P_S3)
X_S3	{IoX_S1}
Y_S3	{IoX_S3}
XY_S3	{XY-S1}; where, XY-S1 = (IoX_S1, IoX_S3)

F_S3	{IF-S1, IF-S2}
P_S3	{(IoX_S1, IF-S1), (IoX_S3, IF-S2)}

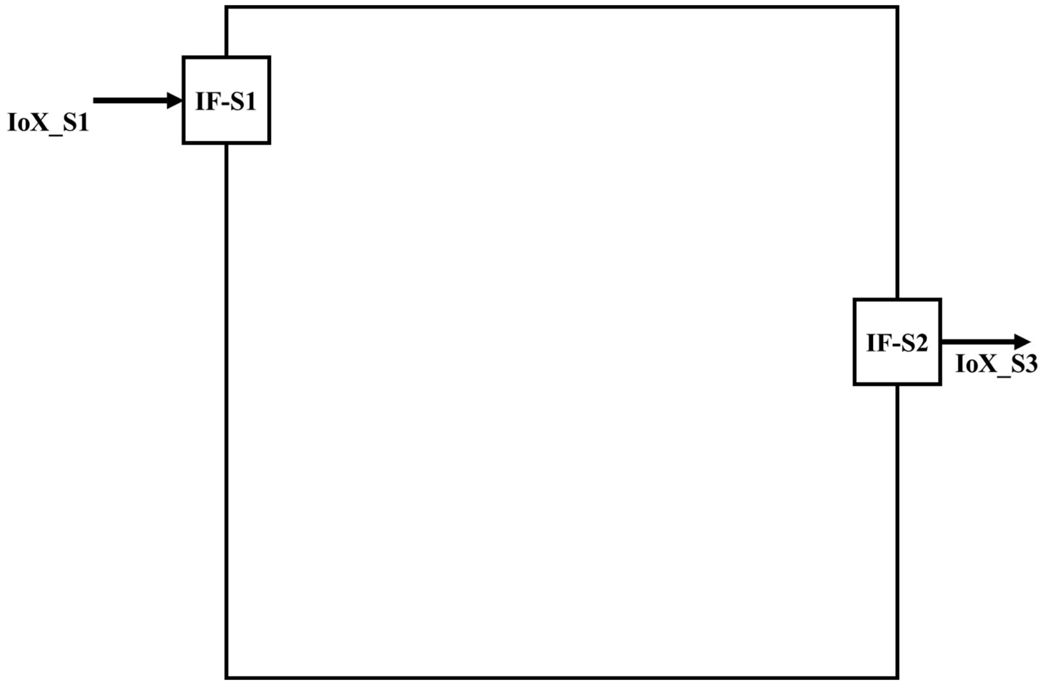

Figure 28: Block diagram description of the problem space of functions 3

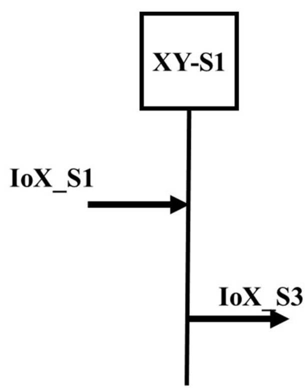

Figure 29: Sequence diagram description of the problem space of functions 3

A.4.4 Problem space of functions 4

Table 128 defines the mathematical structure of the PSF, Figure 30 provides a block diagram representation of IoX-IF mapping for the PSF, and Figure 31 provides a sequence diagram of desired transformation of the PSF.

Table 128: Tabular mathematical specification of a problem space of functions 1 (PSF_S4)

PSF_S4	(X_S4, Y_S4, XY_S4, F_S4, P_S4)
X_S4	{IoX_S2}
Y_S4	{IoX_S4}

XY_S4	{XY-S2}; where, XY-S2 = (IoX_S2, IoX_S4)
F_S4	{IF-S1, IF-S2}
P_S4	{(IoX_S1, IF-S1), (IoX_S2, IF-S1), (IoX_S3, IF-S2), (IoX_S4, IF-S2)}

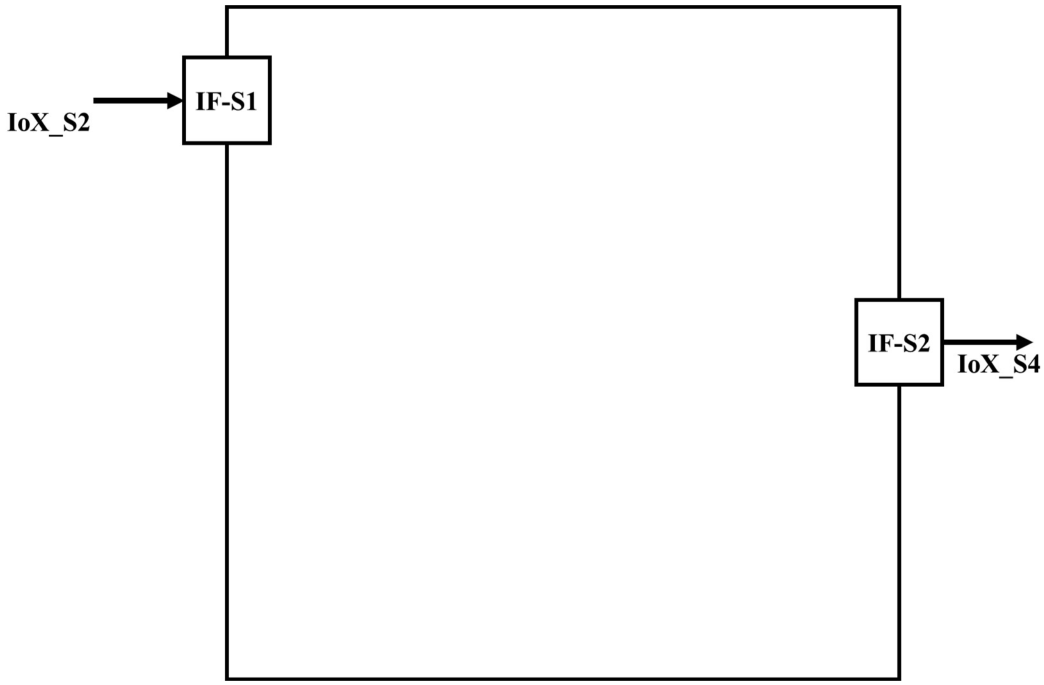

Figure 30: Block diagram description of the problem space of functions 4

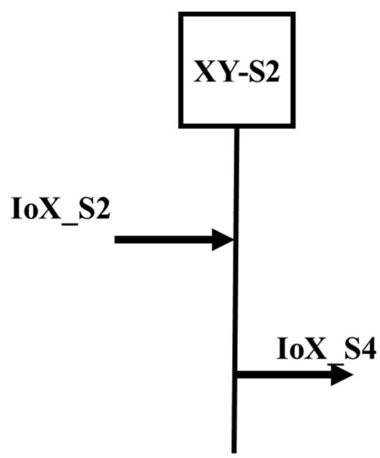

Figure 31: Sequence diagram description of the problem space of functions 4

A.4.5 Problem space of functions 5

Table 129 defines the mathematical structure of the PSF, Figure 32 provides a block diagram representation of IoX-IF mapping for the PSF, and Figure 33 provides a sequence diagram of desired transformation of the PSF.

Table 129: Tabular mathematical specification of a problem space of functions 1 (PSF_S5)

PSF_S5	(X_S5, Y_S5, XY_S5, F_S5, P_S5)
X_S5	{IoX_S1, IoX_S5}
Y_S5	{IoX_S3, IoX_S5}
XY_S5	{XY-S1, XY-S3}; where, XY-S1 = (IoX_S1, IoX_S3) and XY-S3 = (IoX_S5, IoX_S5)
F_S5	{IF-S1, IF-S2, IF-S3}
P_S5	{(IoX_S1, IF-S1), (IoX_S3, IF-S2), (IoX_S5, IF-S3)}

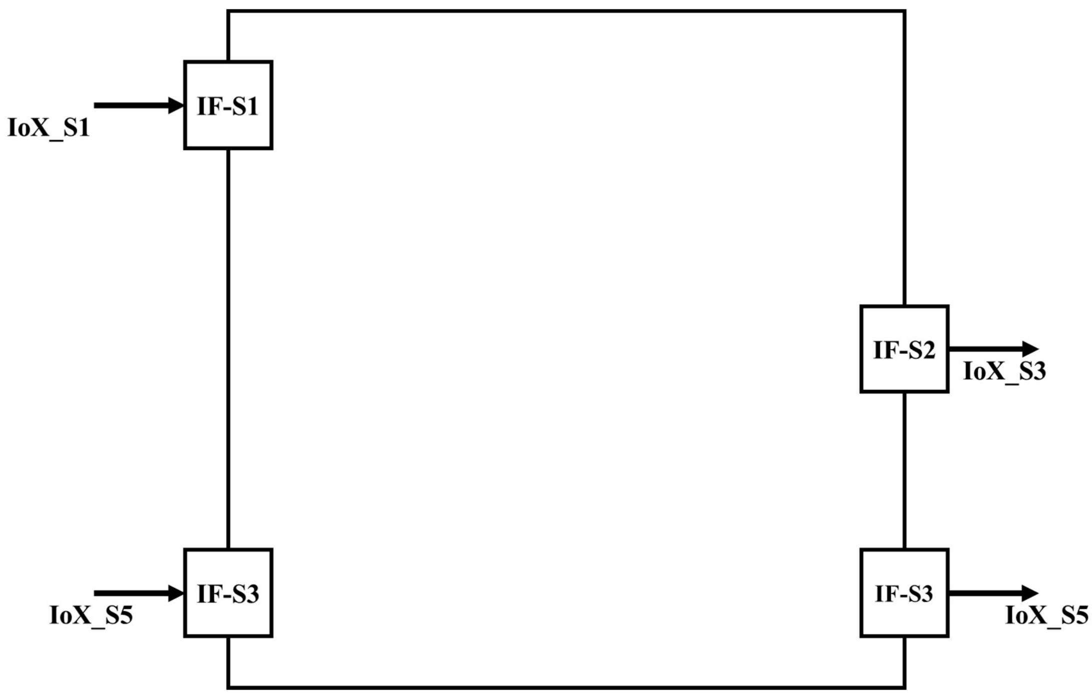

Figure 32: Block diagram description of the problem space of functions 5

Figure 33: Sequence diagram description of the problem space of functions 5

A.4.6 Problem space of functions 6

Table 130 defines the mathematical structure of the PSF, Figure 34 provides a block diagram representation of IoX-IF mapping for the PSF, and Figure 35 provides a sequence diagram of desired transformation of the PSF.

Table 130: Tabular mathematical specification of a problem space of functions 1 (PSF_S6)

PSF_S6	(X_S6, Y_S6, XY_S6, F_S6, P_S6)
X_S6	{IoX_S2, IoX_S5}
Y_S6	{IoX_S4, IoX_S5}
XY_S6	{XY-S2, XY-S3}; where, XY-S2 = (IoX_S2, IoX_S4) and XY-S3 = (IoX_S5, IoX_S5)
F_S6	{IF-S1, IF-S2, IF-S3}
P_S6	{(IoX_S2, IF-S1), (IoX_S4, IF-S2), (IoX_S5, IF-S3)}

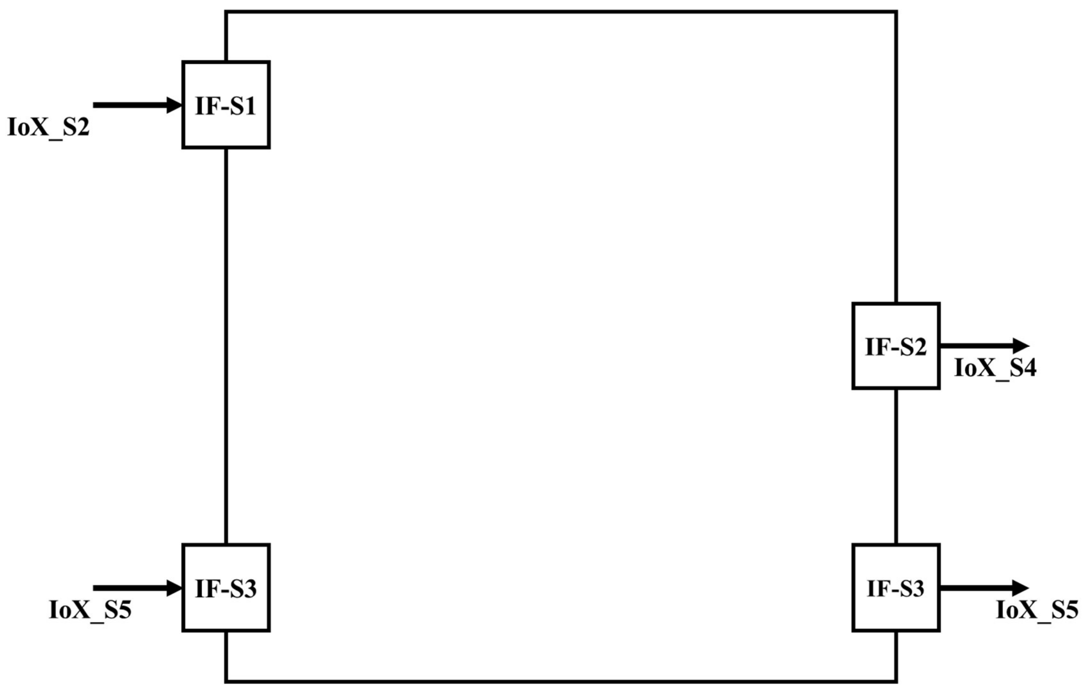

Figure 34: Block diagram description of the problem space of functions 6

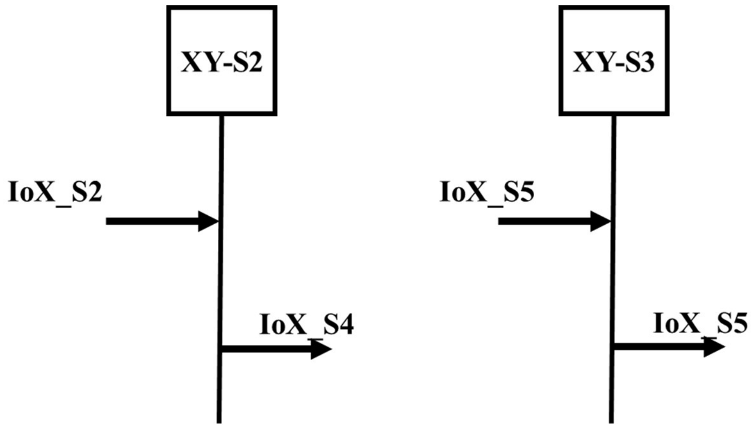

Figure 35: Sequence diagram description of the problem space of functions 6

A.4.7 Problem space of functions 7

Table 131 defines the mathematical structure of the PSF, Figure 36 provides a block diagram representation of IoX-IF mapping for the PSF, and Figure 37 provides a sequence diagram of desired transformation of the PSF.

Table 131: Tabular mathematical specification of a problem space of functions 1 (PSF_S7)

PSF_S7	(X_S7, Y_S7, XY_S7, F_S7, P_S7)
X_S7	{IoX_S5}
Y_S7	{IoX_S5}
XY_S7	{XY-S3}; where, XY-S3 = (IoX_S5, IoX_S5)
F_S7	{IF-S3}
P_S7	{(IoX_S5, IF-S3)}

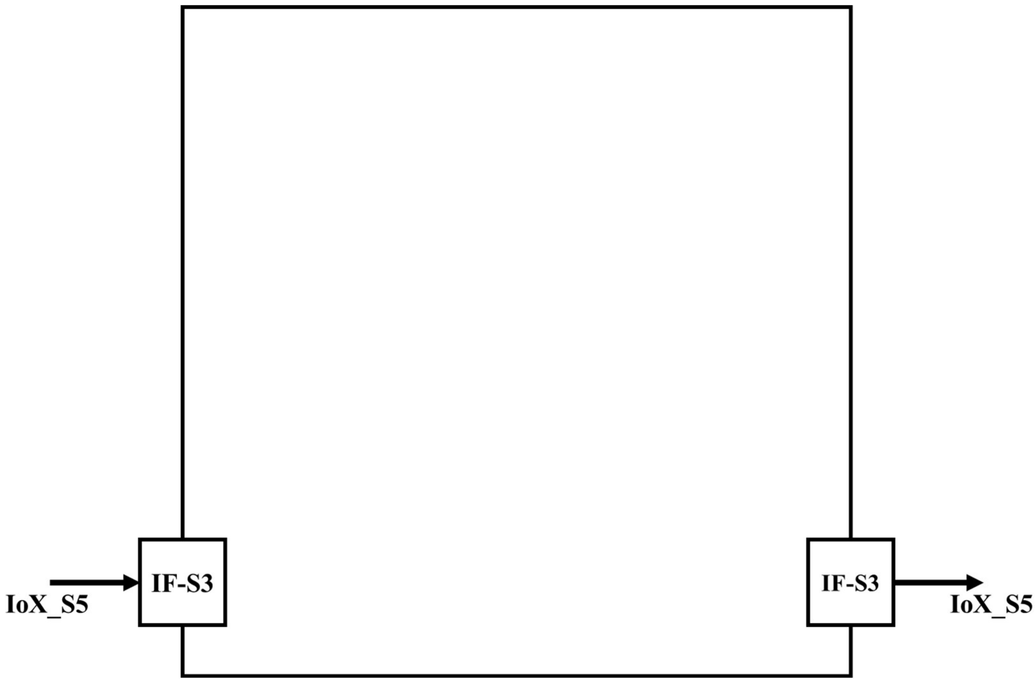

Figure 36: Block diagram description of the problem space of functions 7

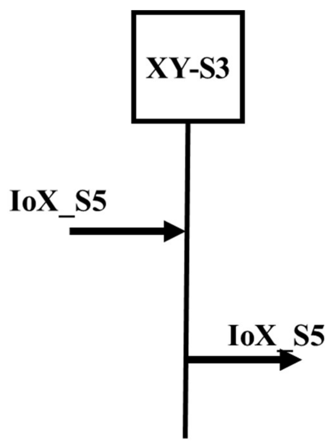

Figure 37: Sequence diagram description of the problem space of functions 7

A.5 Mathematical definition of system models

A.5.1 System model ZA

For system model ZA, Table 132 provides the mathematical description and Figure 38 provides a block diagram with a Moore-based state machine.

Table 132: Tabular mathematical specification of system model ZA

Z_A	(S_A, X_A, Y_A, N_A, R_A, F_A, P_A)
S_A	{S_A1, S_A2}
X_A	{IoX_A1, IoX_A2}
Y_A	{IoX_A3, IoX_A4}

N_A	{((S_A1, IoX_A1), S_A1), ((S_A1, IoX_A2), S_A2), ((S_A2, IoX_A1), S_A1), ((S_A2, IoX_A2), S_A2)}
R_A	{(S_A1, IoX_A3), (S_A2, IoX_A4)}
F_A	{IF-A1, IF-A2}
P_A	{(IoX_A1, IF-A1), (IoX_2, IF-A1), (IoX_A3, IF-A2), (IoX_A4, IF-A2)}

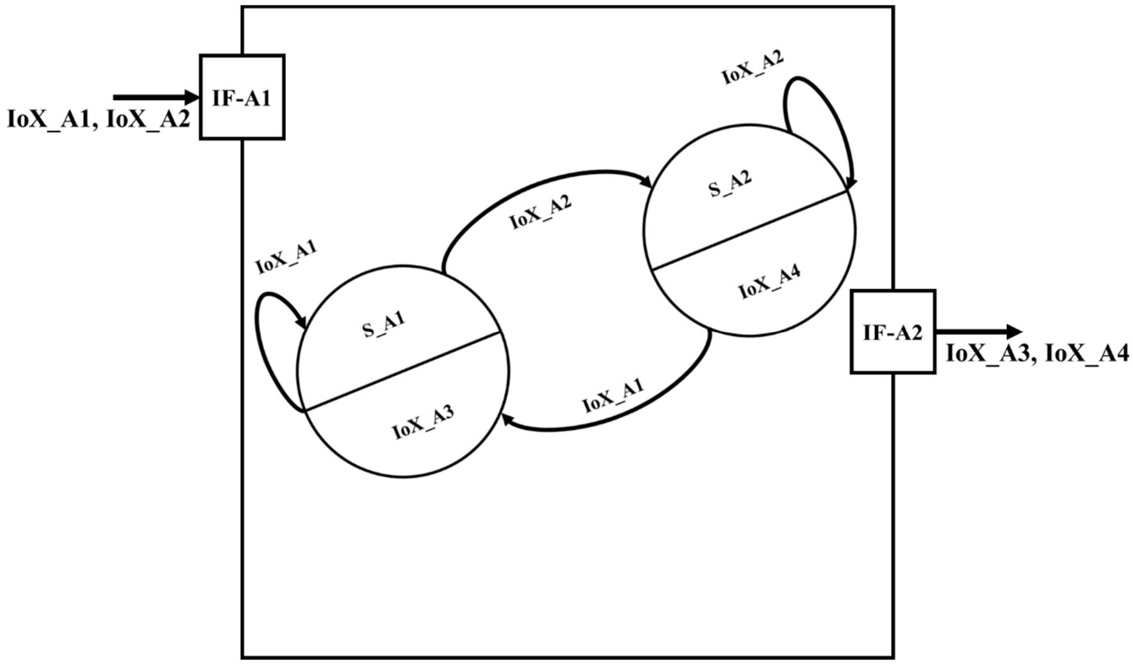

Figure 38: Visual description of system model ZA

A.5.2 System model ZB

For system model ZB, Table 133 provides the mathematical description and Figure 39 provides a block diagram with a Moore-based state machine.

Table 133: Tabular mathematical specification of system model ZB

Z_B	(S_B, X_B, Y_B, N_B, R_B, F_B, P_B)
S_B	{S_B1, S_B2, S_B3}
X_B	{IoX_B1, IoX_B2, IoX_B3, IoX_B4}
Y_B	{IoX_B5, IoX_B6, IoX_B7}
N_B	{((S_B1, IoX_B1), S_B1), ((S_B1, IoX_B2), S_B2), ((S_B1, IoX_B3), S_B1), ((S_B1, IoX_B4), S_B1), ((S_B2, IoX_B1), S_B1), ((S_B2, IoX_B2), S_B2), ((S_B2, IoX_B3), S_B3), ((S_B2, IoX_B4), S_B2), ((S_B3, IoX_B1), S_B3), ((S_B3, IoX_B2), S_B3), ((S_B3, IoX_B3), S_B3), ((S_B3, IoX_B4), S_B2)}
R_B	{(S_B1, IoX_B5), (S_B2, IoX_B6), (S_B3, IoX_B7)}
F_B	{IF-B1, IF-B2}
P_B	{(IoX_B1, IF-B1), (IoX_B2, IF-B1), (IoX_B3, IF-B1), (IoX_B4, IF-B1), (IoX_B5, IF-B2), (IoX_B6, IF-B2), (IoX_B7, IF-B2)}

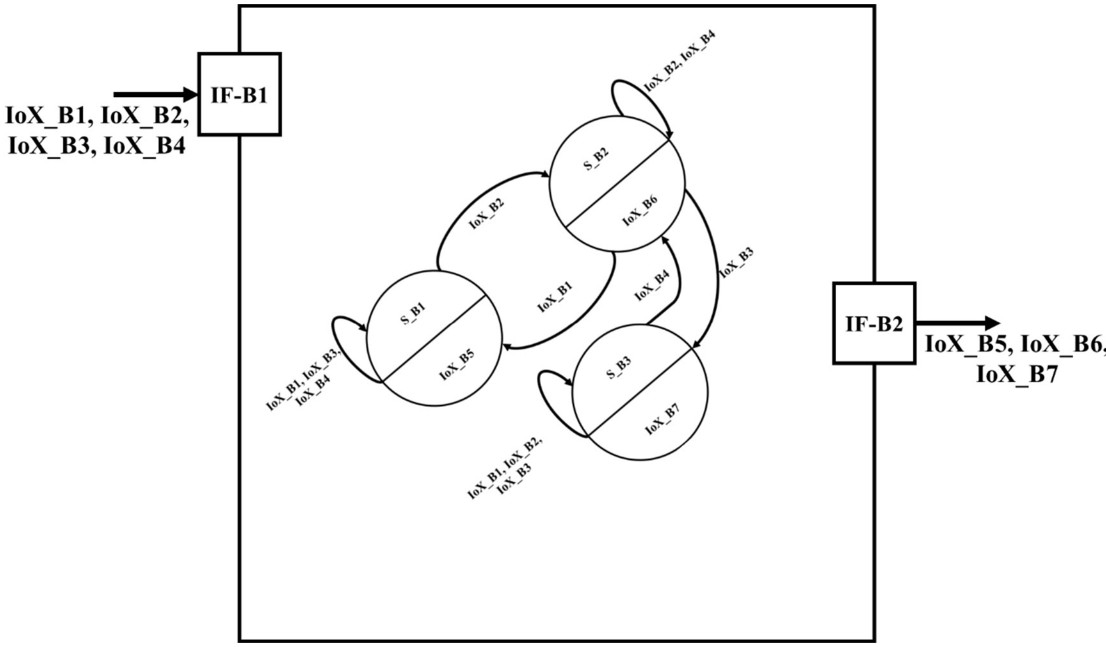

Figure 39: Visual description of system model ZB

A.5.3 System model ZC

For system model ZC, Table 134 provides the mathematical description and Figure 40 provides a block diagram with a Moore-based state machine.

Table 134: Tabular mathematical specification of system model ZC

Z_C	(S_C, X_C, Y_C, N_C, R_C, F_C, P_C)
S_C	{S_C1}
X_C	{IoX_C1}
Y_C	{IoX_C1}
N_C	{((S_C1, IoX_C1), S_C1)}
R_C	{(S_C1, IoX_C1)}
F_C	{IF-C1}
P_C	{(IoX_C1, IF-C1)}

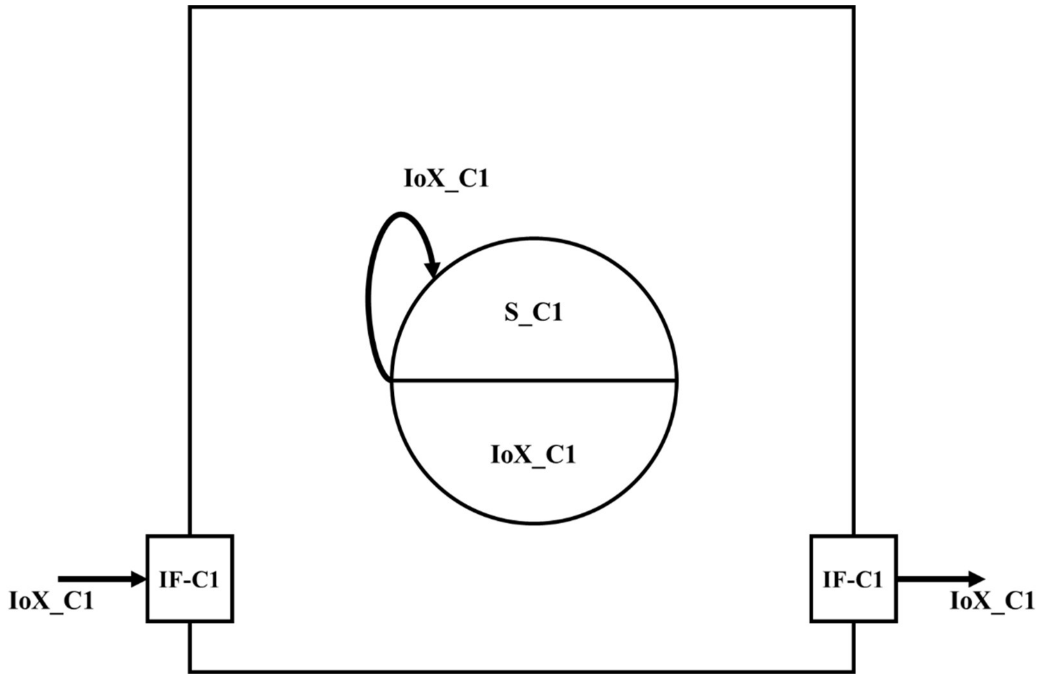

Figure 40: Visual description of system model ZC

A.5.4 System model ZAD

For system model ZAD, Table 135 provides the mathematical description and Figure 41 provides a block diagram with a Moore-based state machine.

Table 135: Tabular mathematical specification of system model ZAD

Z_AD	(S_AD, X_AD, Y_AD, N_AD, R_AD, F_AD, P_AD)
S_AD	{S_AD1, S_AD2}
X_AD	{IoX_A1, IoX_A2}
Y_AD	{IoX_A5, IoX_A6}
N_AD	{((S_AD1, IoX_A1), S_AD1), ((S_AD1, IoX_A2), S_AD2), ((S_AD2, IoX_A1), S_AD1), ((S_AD2, IoX_A2), S_AD2)}
R_AD	{(S_AD1, IoX_A5), (S_AD2, IoX_A6)}
F_AD	{IF-A1, IF-A3}
P_AD	{(IoX_A1, IF-A1), (IoX_A2, IF-A1), (IoX_A5, IF-A3), (IoX_A6, IF-A3)}

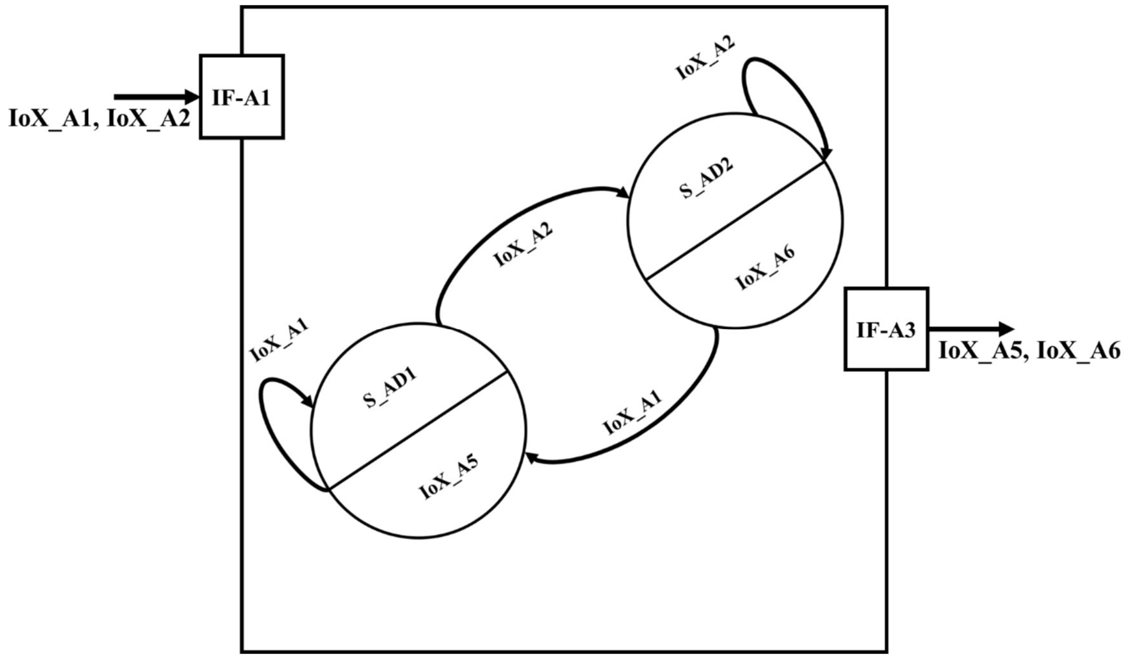

Figure 41: Visual description of system model ZAD

A.5.5 System model ZAE

For system model ZAE, Table 136 provides the mathematical description and Figure 42 provides a block diagram with a Moore-based state machine.

Table 136: Tabular mathematical specification of system model ZAE

Z_AE	(S_AE, X_AE, Y_AE, N_AE, R_AE, F_AE, P_AE)
S_AE	{S_AE1, S_AE2}
X_AE	{IoX_A5, IoX_A6}
Y_AE	{IoX_A3, IoX_A4}
N_AE	{((S_AE1, IoX_A5), S_AE1), ((S_AE1, IoX_A6), S_AE2), ((S_AE2, IoX_A5), S_AE1), ((S_AE2, IoX_A6), S_AE2)}
R_AE	{(S_AE1, IoX_A3), (S_AE2, IoX_A4)}
F_AE	{IF-A2, IF-A3}
P_AE	{(IoX_A5, IF-A3), (IoX_A6, IF-A3), (IoX_A3, IF-A2), (IoX_A4, IF-A2)}

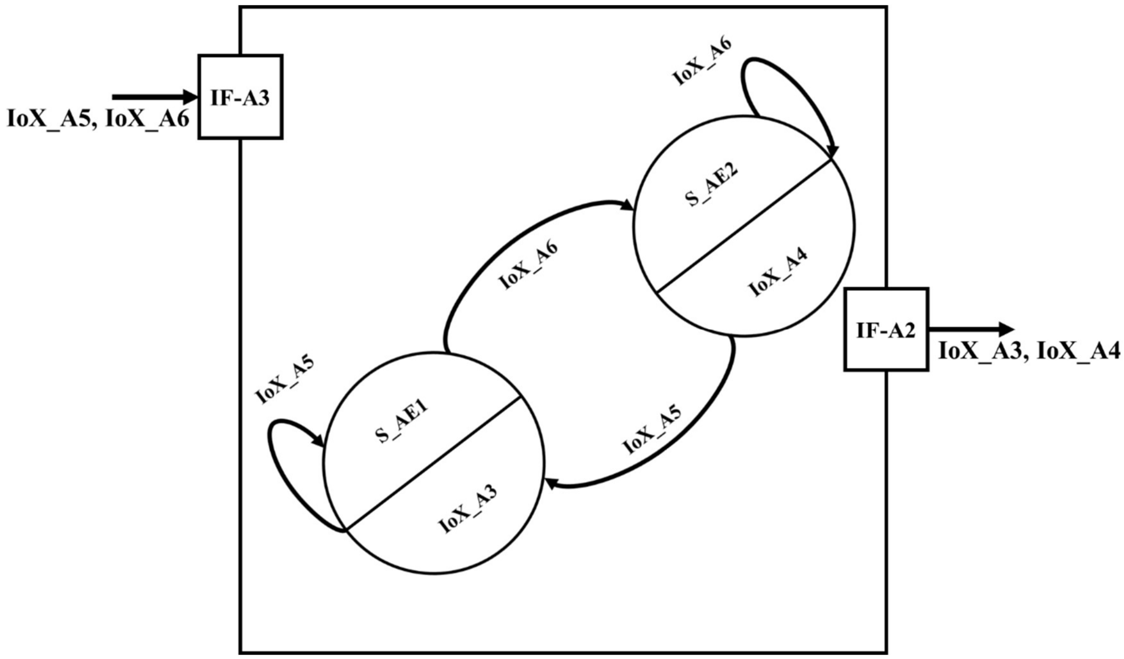

Figure 42: Visual description of system model ZAE

A.5.6 System model ZBD

For system model ZBD, Table 137 provides the mathematical description and Figure 43 provides a block diagram with a Moore-based state machine.

Table 137: Tabular mathematical specification of system model ZBD

Z_BD	(S_BD, X_BD, Y_BD, N_BD, R_BD, F_BD, P_BD)
S_BD	{S_BD1, S_BD2, S_BD3}
X_BD	{IoX_B1, IoX_B2, IoX_B3, IoX_B4}
Y_BD	{IoX_B8, IoX_B9, IoX_B10}
N_BD	{((S_BD1, IoX_B1), S_BD1), ((S_BD1, IoX_B2), S_BD2), ((S_BD1, IoX_B3), S_BD1), ((SBD1, IoX_B4), SBD1), ((S2, IoX_BD1), SBD1), ((SBD2, IoX_B2), SBD2), ((SBD2, IoX_B3), S_BD3), ((S_BD2, IoX_B4), S_BD2), ((S_BD3, IoX_B1), SBD3), ((S_BD3, IoX_B2), S_BD3), ((S_BD3, IoX_B3), S_BD3), ((S_BD3, IoX_B4), S_BD2)}
R_BD	{(S_BD1, IoX_B8), (S_BD2, IoX_B9), (S_BD3, IoX_B10)}
P_BD	{IF-B1, IF-B3}
F_BD	{(IoX_B1, IF-B1), (IoX_B2, IF-B1), (IoX_B3, IF-B1), (IoX_B4, IF-B1) (IoX_B8, IF-B3), (IoX_B9, IF-B3), (IoX_B10, IF-B3)}

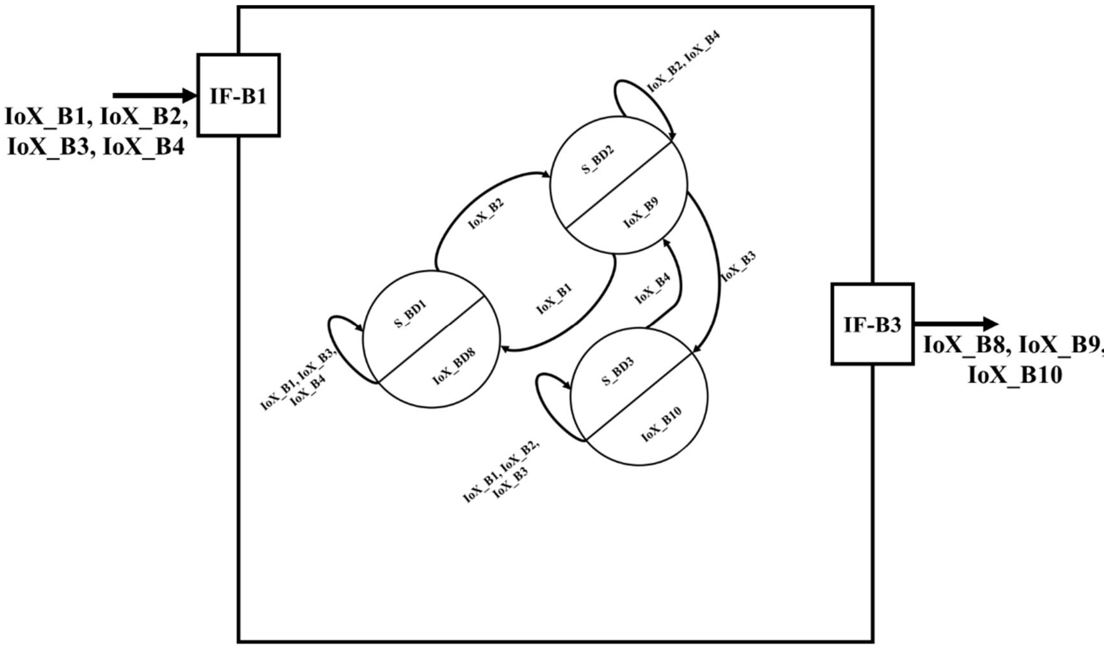

Figure 43: Visual description of system model ZBD

A.5.7 System model ZBE

For system model ZBE, Table 138 provides the mathematical description and Figure 44 provides a block diagram with a Moore-based state machine.

Table 138: Tabular mathematical specification of system model ZBE

Z_BE	(S_BE, X_BE, Y_BE, N_BE, R_BE, F_BE, P_BE)
S_BE	{S_BE1, S_BE2, S_BE3}
X_BE	{IoX_B8, IoX_B9, IoX_B10}
Y_BE	{IoX_B5, IoX_B6, IoX_B7}
N_BE	{((S_BE1, IoX_B8), S_BE1), ((S_BE1, IoX_B9), S_BE2), ((S_BE1, IoX_B10), S_BE1), ((S_BE2, IoX_B8), S_BE1), ((S_BE2, IoX_B9), S_BE2), ((S_BE2, IoX_B10), S_B3), ((S_BE3, IoX_B8), S_BE3), ((S_BE3, IoX_B9), S_BE2), ((S_BE3, IoX_B10), S_BE3)}
R_BE	{(S_BE1, IoX_B5), (S_BE2, IoX_B6), (S_BE3, IoX_B7)}
F_BE	{IF-B2, IF-B3}
P_BE	{(IoX_B5, IF-B2), (IoX_B6, IF-B2), (IoX_B7, IF-B2), (IoX_B8, IF-B3), (IoX_B9, IF-B3), (IoX_B10, IF-B3)}

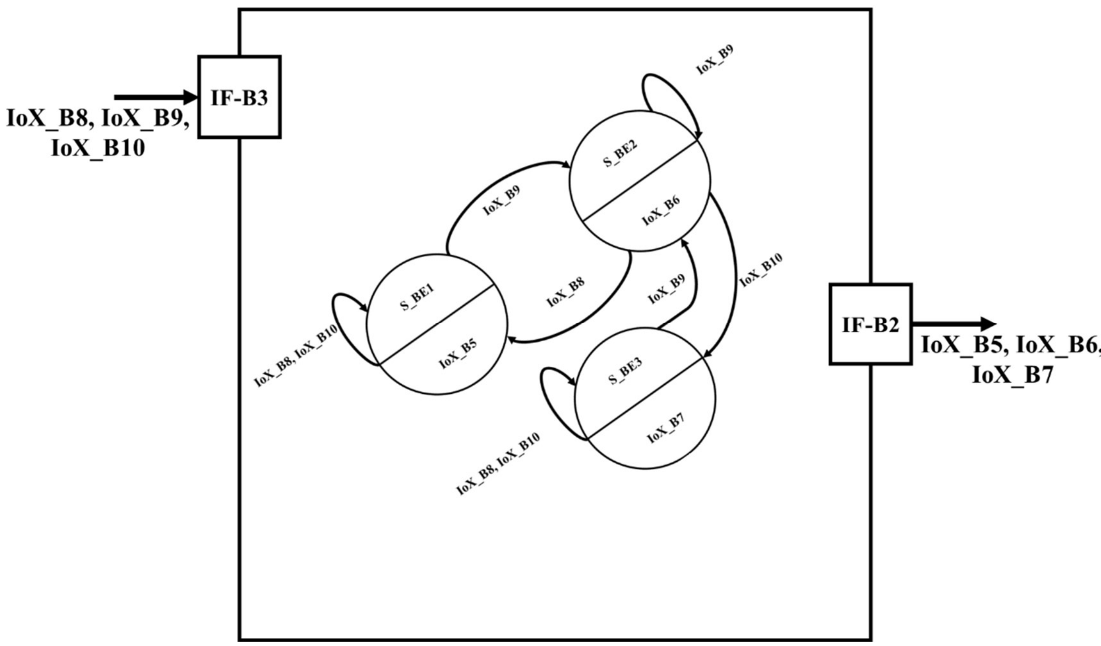

Figure 44: Visual description of system model ZBE

A.5.8 System model ZA2

For system model ZA2, Table 139 provides the mathematical description, Figure 45 provides a block diagram at L2, and Figure 46 provides block diagram with a Moore-based state machine of the resultant at L1.

Table 139: Tabular mathematical specification of system model ZA2

Z_A2	(SCR_A2, Z_A@)
SCR_A2	{((Z_AD, Z_AE), (IoX_A5, IF-A3)), ((Z_AD, Z_AE), (IoX_A6, IF-A3))}
Z_A@	(S_A@, X_A@, Y_A@, N_A@, R_A@, F_A@, P_A@)
SZ_A@	{SA@1, SA@2}
IZ_A@	{IoX_A1, IoX_A2}
OZ_A@	{IoX_A3, IoX_A4}
NZ_A@	{((SA@1, IoX_A1), SA@1), ((SA@1, IoX_A2), SA@2), ((SA@2, IoX_A1), SA@1), ((SA@2, IoX_A2), SA@2)}
RZ_A@	{(SA@1, IoX_A3), (SA@2, IoX_A4)}
F_A@	{IF-A1, IF-A2}
P_A@	{(IoX_A1, IF-A1), (IoX_A2, IF-A1), (IoX_A3, IF-A2), (IoX_A4, IF-A2)}

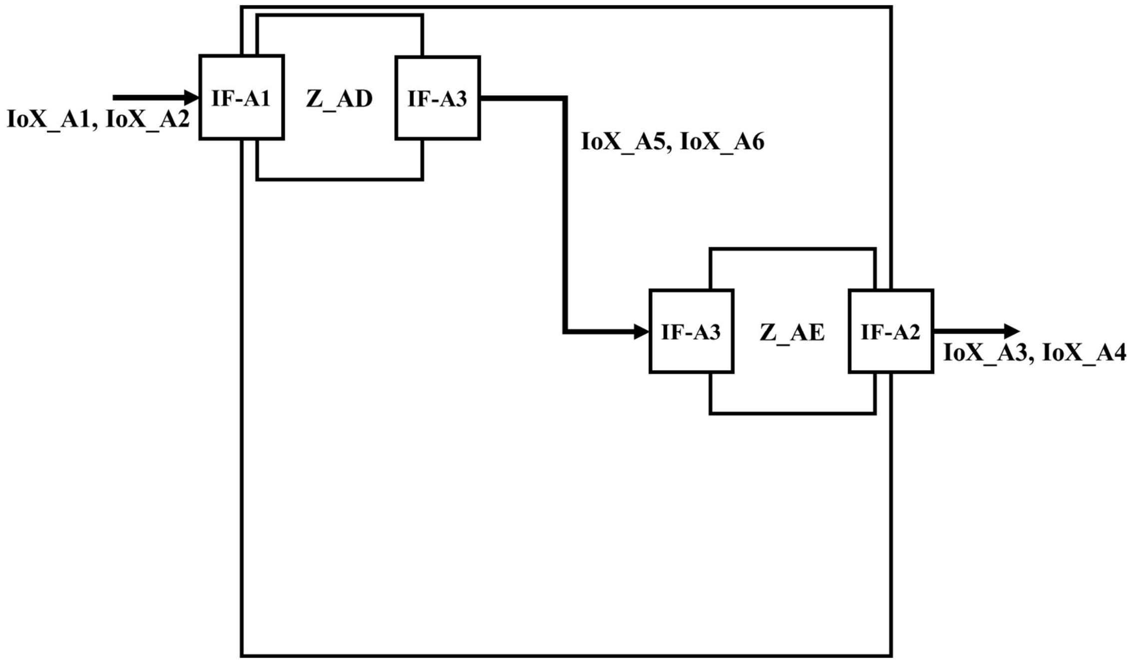

Figure 45: Visual description of system model ZA2 at level 2

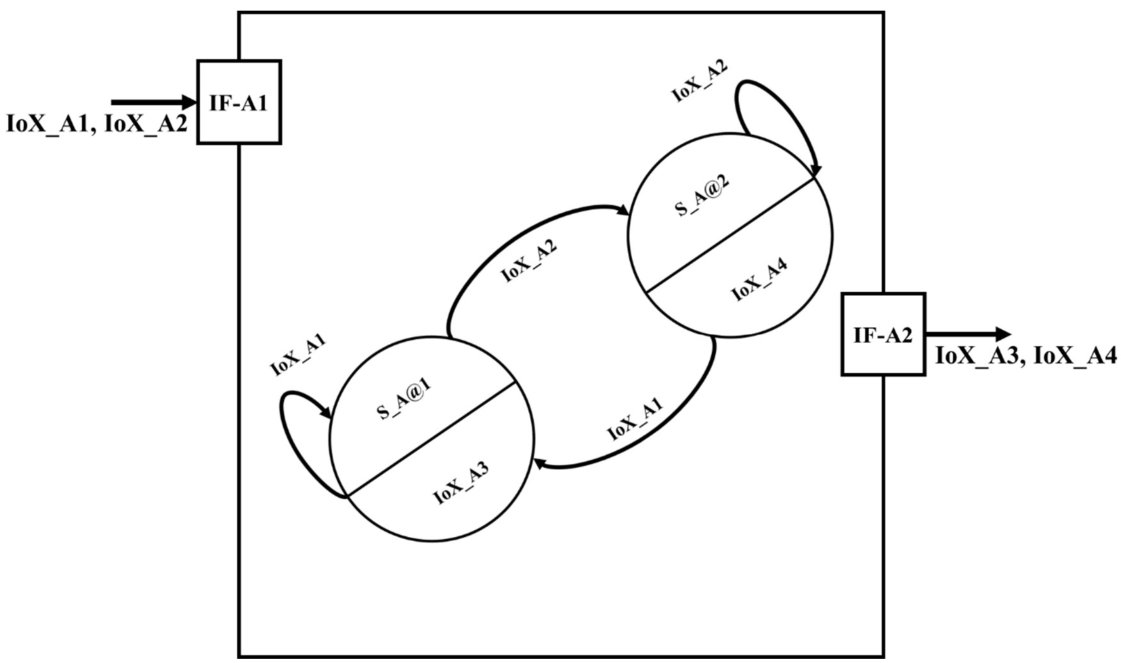

Figure 46: Visual description of resultant system model ZA@ at level 1

A.5.9 System model ZB2

For system model ZB2, Table 140 provides the mathematical description, Figure 47 provides a block diagram at L2, and Figure 48 provides block diagram with a Moore-based state machine of the resultant at L1.

Table 140: Tabular mathematical specification of system model ZB2

Z_B2	(SCR_B2, Z_B@)
SCR_B2	{((Z_BD, Z_BE), (IoX_B8, IF-B3)), ((Z_BD, Z_BE), (IoX_B9, IF-B3)), ((Z_BD, Z_BE), (IoX_B10, IF-B3))}
Z_B@	(SZ_B@, IZ_B@, OZ_B@, NZ_B@, RZ_B@)
S_B@	{S_B@1, S_B@2, S_B@3}
X_B@	{IoX_B1, IoX_B2, IoX_B3, IoX_B4}
Y_B@	{IoX_B5, IoX_B6, IoX_B7}
N_B@	{((S_B@1, IoX_B1), S_B@1), ((S_B@1, IoX_B2), S_B@2), ((S_B@1, IoX_B3), S_B@1), ((S_B@1, IoX_B@4), S_B@1), ((S_B@2, IoX_B1), S_B@1), ((S_B@2, IoX_B2), S_B@2), ((S_B@2, IoX_B3), S_B@3), ((S_B@2, IoX_B4), S_B@2), ((S_B@3, IoX_B1), S_B@3), ((S_B@3, IoX_B2), S_B@3), ((S_B@3, IoX_B3), S_B@3), ((S_B@3, IoX_B4), S_B@2)}
R_B@	{(S_B@1, IoX_B5), (S_B@2, IoX_B6), (S_B@3, IoX_B7)}
F_B@	{IF-B1, IF-B2}
P_B@	{(IoX_B1, IF-B1), (IoX_B2, IF-B1), (IoX_B3, IF-B1), (IoX_B4, IF-B1), (IoX_B5, IF-B2), (IoX_B6, IF-B2), (IoX_B7, IF-B1)}

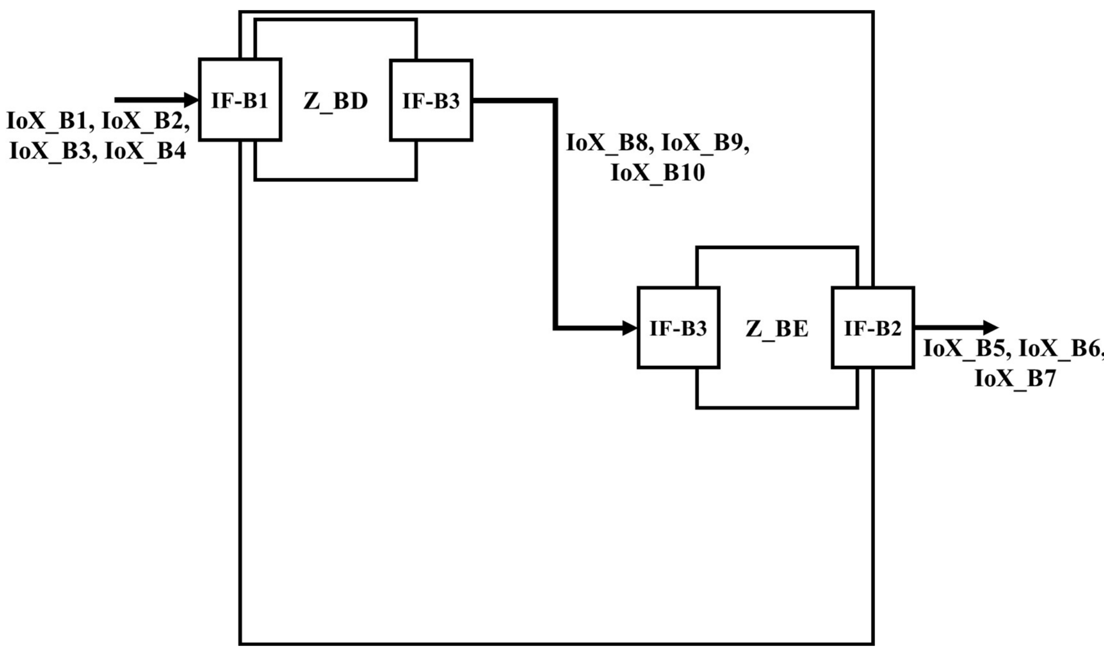

Figure 47: Visual description of system model ZB2 at level 2

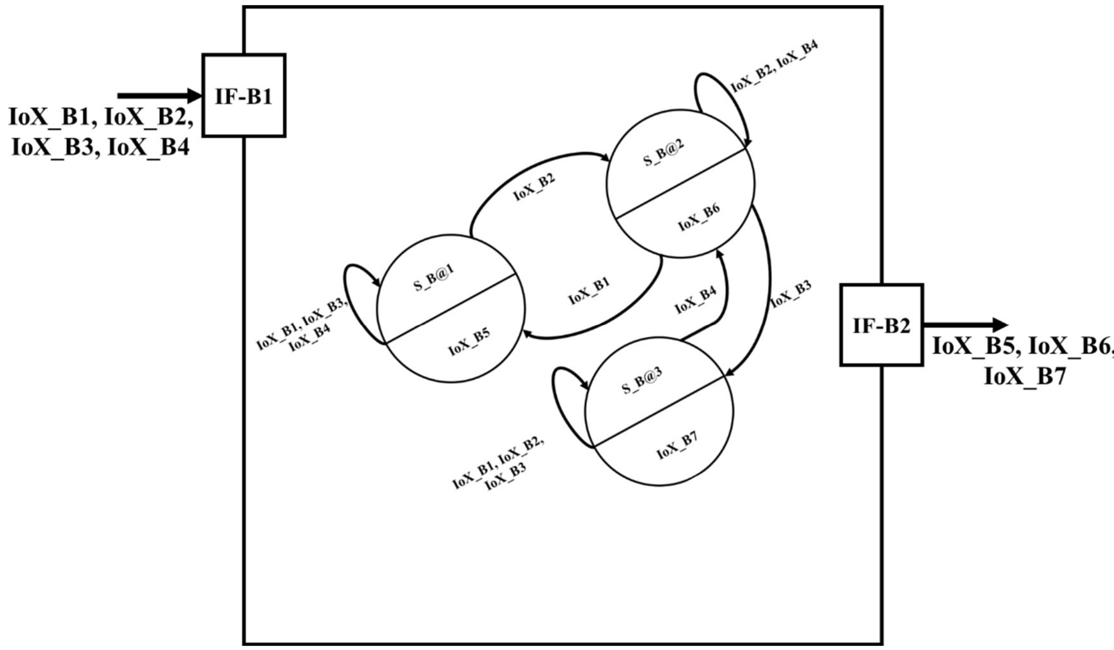

Figure 48: Visual description of resultant system model ZB@ at level 1

A.5.10 System model ZAC1

For system model ZAC1, Table 141 provides the mathematical description and Figure 49 provides a block diagram with a Moore-based state machine.

Table 141: Tabular mathematical specification of system model ZAC1

Z_AC1	(S_AC1, X_AC1, Y_AC1, N_AC1, R_AC1, F_AC1, P_AC1)
S_AC1	{S_AC1, S_AC2}
X_AC1	{(IoX_A1, IoX_C1), (IoX_A2, IoX_C1)}
Y_AC1	{(IoX_A3, IoX_C1), (IoX_A4, IoX_C1)}
N_AC1	{((S_A1, (IoX_A1, IoX_C1)), S_A1), ((S_A1, (IoX_A2, IoX_C1)), S_A2), ((S_A2, (IoX_A1, IoX_C1)), S_A1), ((S_A2, (IoX_A2, IoX_C1)), S_A2)}
R_AC1	{(S_A1, (IoX_A3, IoX_C1)), (S_A2, (IoX_A4, IoX_C1))}
F_AC1	{IF-A1, IF-A2, IF-C1}
P_AC1	{(IoX_A1, IF-A1), (IoX_2, IF-A1), (IoX_A3, IF-A2), (IoX_A4, IF-A2), (IoX_C1, IF-C1)}

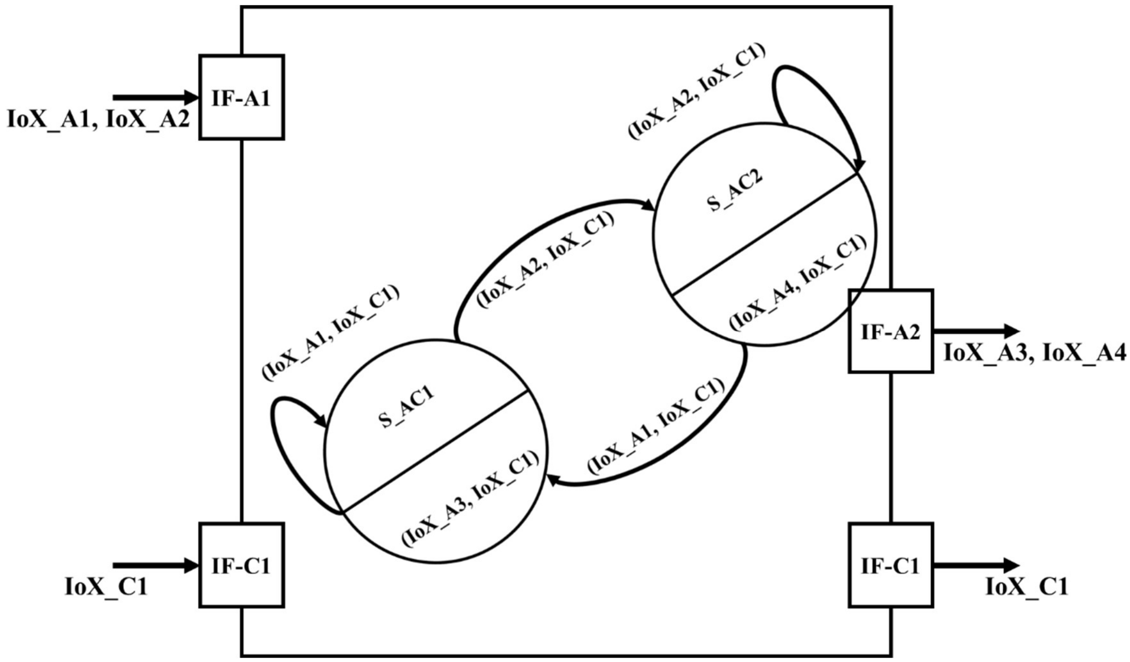

Figure 49: Visual description of system model ZAC1

A.5.11 System model ZAC2

For system model ZAC2, Table 142 provides the mathematical description, Figure 50 provides a block diagram at L2, and Figure 51 provides block diagram with a Moore-based state machine of the resultant at L1.

Table 142: Tabular mathematical specification of system model ZAC2

Z_AC2	(SCR_AC2, Z_AC@)
SCR_AC2	{((Z_AD, Z_AE), (IoX_A5, IF-A3)), ((Z_AD, Z_AE), (IoX_A6, IF-A3)), ((Z_AD, Z_C), Ø), ((Z_AE, Z_C), Ø)}
Z_AC@	(SZ_AC@, IZ_AC@, OZ_AC@, NZ_AC@, RZ_AC@)
S_AC@	{S_AC@1, S_AC@2}
X_AC@	{(IoX_A1, IoX_C1), (IoX_A2, IoX_C1)}
Y_AC@	{(IoX_A3, IoX_C1), (IoX_A4, IoX_C1)}
N_AC@	{((S_AC@1, (IoX_A1, IoX_C1)), S_AC@1), ((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2), ((S_AC@2, (IoX_A1, IoX_C1)), S_AC@1), ((S_AC@2, (IoX_A2, IoX_C1)), S_AC@2)}
R_AC@	{(S_AC@1, (IoX_A3, IoX_C1)), (S_AC@2, (IoX_A4, IoX_C1))}
F_AC@	{IF-A1, IF-A2, IF-C1}
P_AC@	{(IoX_A1, IF-A1), (IoX_A2, IF-A1), (IoX_A3, IF-A2), (IoX_A4, IF-A2), (IoX_C1, IF-C1)}

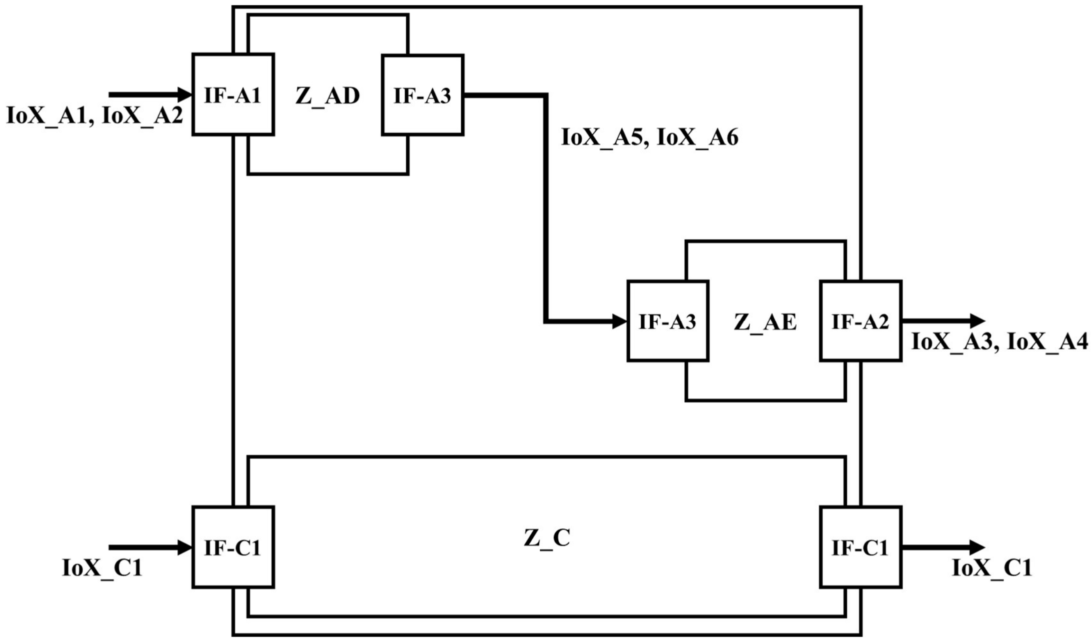

Figure 50: Visual description of system model ZAC2 at level 2

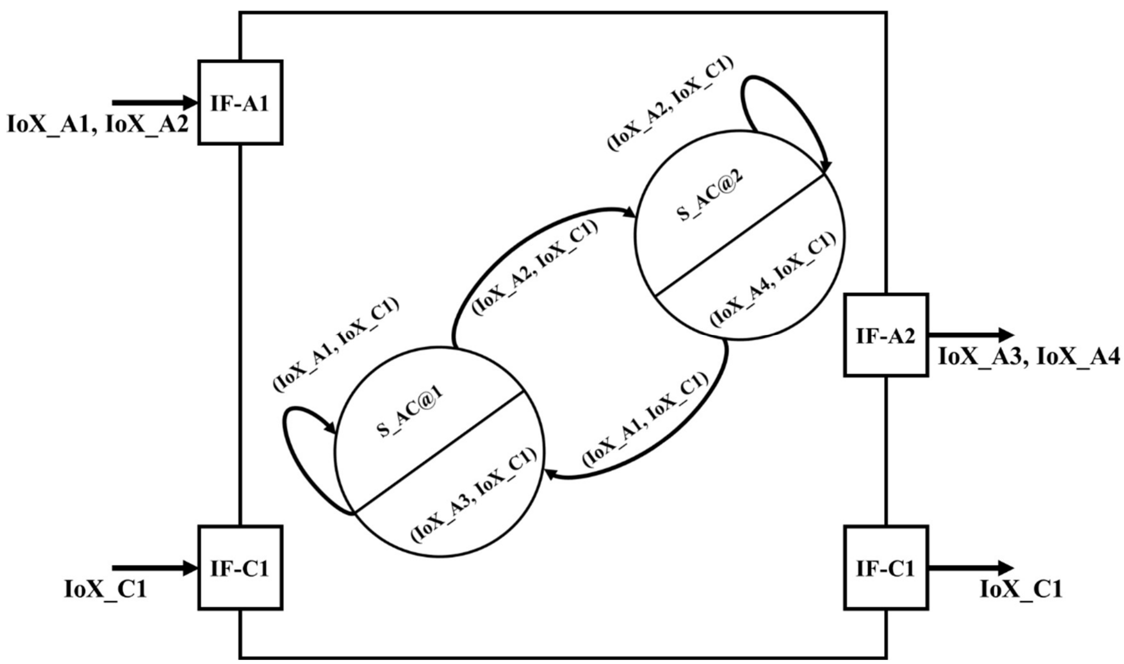

Figure 51: Visual description of resultant system model ZAC@ at level 1

A.5.12 System model ZBC1

For system model ZBC1, Table 143 provides the mathematical description and Figure 52 provides a block diagram with a Moore-based state machine.

Table 143: Tabular mathematical specification of system model ZBC1

Z_BC1	(S_BC1, X_BC1, Y_BC1, N_BC1, R_BC1, F_BC1, P_BC1)
S_BC1	{S_BC1, S_BC2, S_BC3}

X_BC1	{(IoX_B1, IoX_C1), (IoX_B2, IoX_C1), (IoX_B3, IoX_C1), (IoX_B4, IoX_C1)}
Y_BC1	{(IoX_B5, IoX_C1), (IoX_B6, IoX_C1), (IoX_B7, IoX_C1)}
N_BC1	{((S_B1, (IoX_B1, IoX_C1)), S_B1), ((S_B1, (IoX_B2, IoX_C1)), S_B2), ((S_B1, (IoX_B3, IoX_C1)), S_B1), ((S_B1, (IoX_B4, IoX_C1)), S_B1), ((S_B2, (IoX_B1, IoX_C1)), S_B1), ((S_B2, (IoX_B2, IoX_C1)), S_B2), ((S_B2, (IoX_B3, IoX_C1)), S_B3), ((S_B2, (IoX_B4, IoX_C1)), S_B2), ((S_B3, (IoX_B1, IoX_C1)), S_B3), ((S_B3, (IoX_B2, IoX_C1)), S_B3), ((S_B3, (IoX_B3, IoX_C1)), S_B3), ((S_B3, (IoX_B4, IoX_C1)), S_B2)}
R_BC1	{(S_B1, (IoX_B5, IoX_C1)), (S_B2, (IoX_B6, IoX_C1)), (S_B3, (IoX_B7, IoX_C1))}
F_BC1	{IF-B1, IF-B2, IF-C1}
P_BC1	{(IoX_B1, IF-B1), (IoX_B2, IF-B1), (IoX_B3, IF-B1), (IoX_B4, IF-B1), (IoX_B5, IF-B2), (IoX_B6, IF-B2), (IoX_B7, IF-B2), (IoX_C1, IF-C1)}

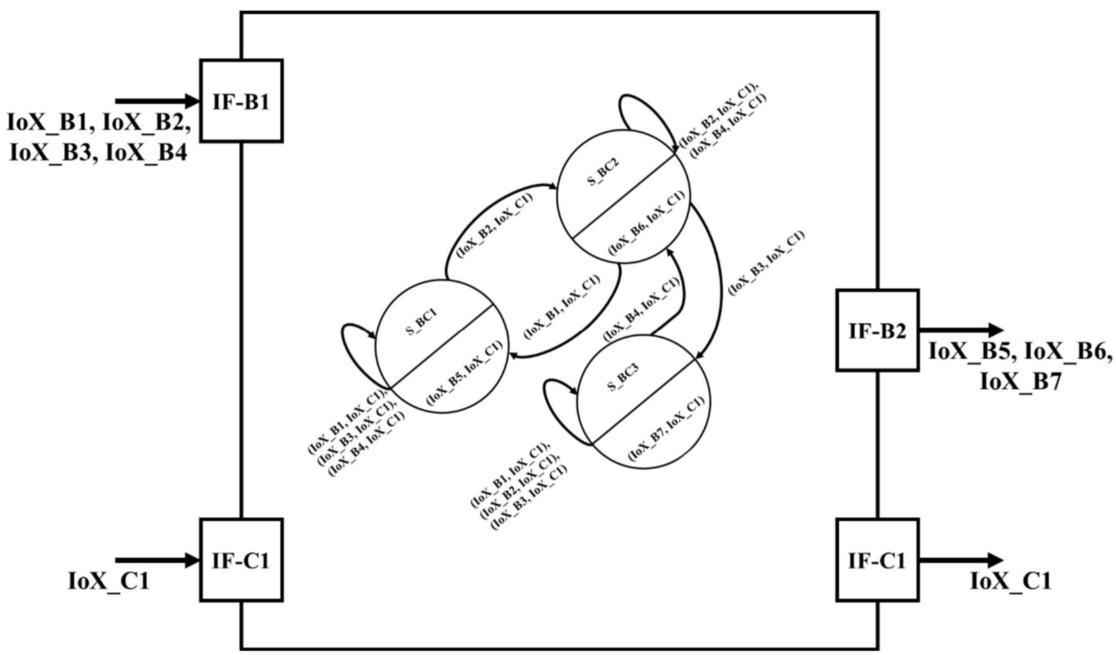

Figure 52: Visual description of system model ZBC1

A.5.13 System model ZBC2

For system model ZBC2, Table 144 provides the mathematical description, Figure 53 provides a block diagram at L2, and Figure 54 provides block diagram with a Moore-based state machine of the resultant at L1.

Table 144: Tabular mathematical specification of system model ZBC2

Z_BC2	(SCR_BC2, Z_BC@)
SCR_BC2	{((Z_BD, Z_BE), (IoX_B8, IF-B3)) ((Z_BD, Z_BE), (IoX_B9, IF-B3)), ((Z_BD, Z_BE), (IoX_B10, IF-B3)), ((Z_BD, Z_C), Ø), (Z_BE, Z_C), Ø)}
Z_BC@	(S_BC@, X_BC@, Y_BC@, N_BC@, R_BC@, F_BC@, P_BC@)

S_BC@	{S_BC@1, S_BC@2, S_BC@3}
X_BC@	{IoX_B1, IoX_B2, IoX_B3, IoX_B4, IoX_C1}
Y_BC@	{IoX_B5, IoX_B6, IoX_B7, IoX_C1}
N_BC@	{((S_BC@1, (IoX_B1, IoX_C1)), S_BC@1), ((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@1, (IoX_B3, IoX_C1)), S_BC@1), ((S_BC@1, (IoX_B@4, IoX_C1)), S_BC@1), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1), ((S_BC@2, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@2, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@3, (IoX_B1, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B2, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)}
R_BC@	{(S_BC@1, (IoX_B5, IoX_C1)), (S_BC@2, (IoX_B6, IoX_C1)), (S_BC@3, (IoX_B7, IoX_C1))}
F_BC@	{IF-B1, IF-B2, IF-C1}
P_BC@	{(IoX_B1, IF-B1), (IoX_B2, IF-B1), (IoX_B3, IF-B1), (IoX_B4, IF-B1), (IoX_B5, IF-B2), (IoX_B6, IF-B2), (IoX_B7, IF-B1), (IoX_C1, IF-C1)}

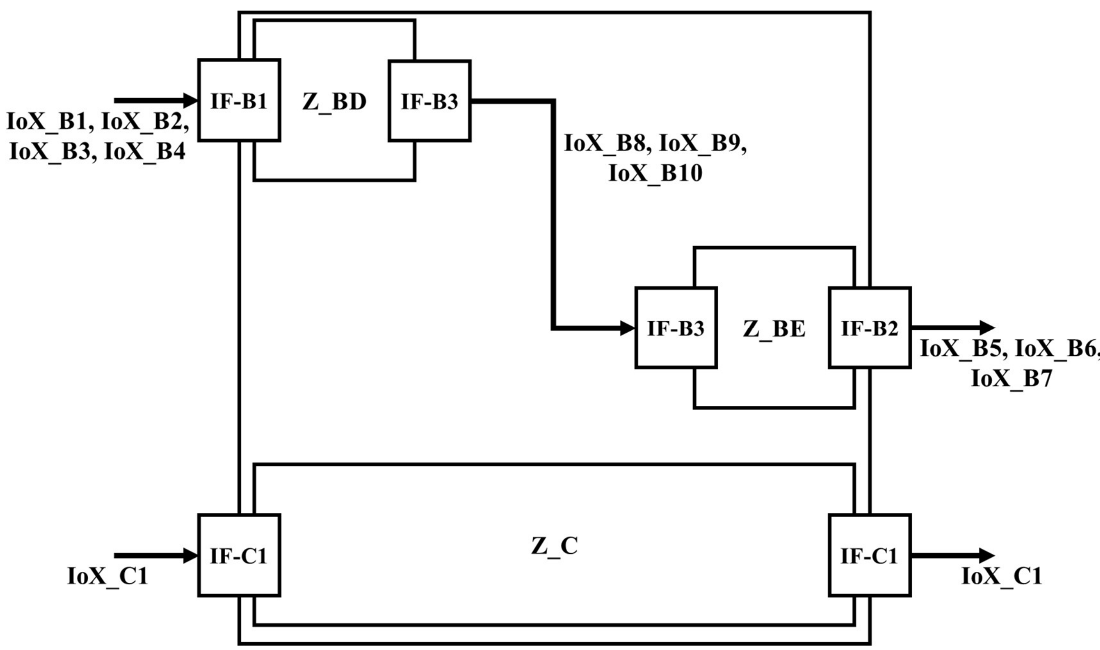

Figure 53: Visual description of system model ZBC2 at level 2

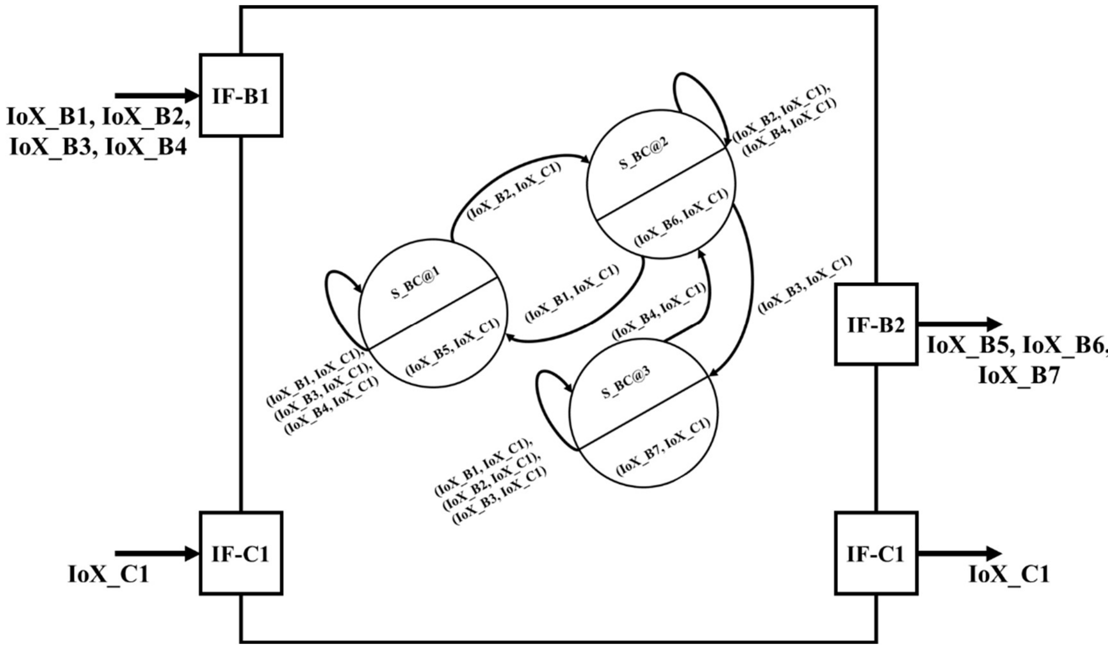

Figure 54: Visual description of resultant system model ZBC@ at level 1

A.6 Supporting results of definition of SM from PSF

A.6.1 ZA definition from PSF

Table 145 provides IoX mapping, Table 146 provides IF mapping, Table 147 provides IoX-IF mapping, and Table 148 provides mapping between XY function of PSF to next state (N) and final readout (R) functions of the SM. From the result, the SM may be defined PSF_S2, PSF_S3, and PSF_4 and may not be defined from PSF_S1, PSF_S5, PSF_S6, or PSF_S7. The result was validated through the DEVS simulations in MS4 Me.

Table 145: Item of exchange (IoX) mapping from PSF to system model ZA

PSF	ZA
IoX_S1	IoX_A1
IoX_S2	IoX_A2
IoX_S3	IoX_A3
IoX_S4	IoX_A4
IoX_S5	N/A

Table 146: Interface (IF) mapping from PSF to system model ZA

PSF	ZA
IF-S1	IF-A1
IF-S2	IF-A2
IF-S3	N/A

Table 147: IoX and IF paired mapping from PSF to system model ZA

PSF	ZA
(IoX_S1, IF-S1)	(IoX_A1, IF-Al)
(IoX_S2, IF-S1)	(IoX_A2, IF-A1)
(IoX_S3, IF-S2)	(IoX_A3, IF-A2)
(IoX_S4, IF-S2)	(IoX_A4, IF-A2)
(IoX_S5, IF-S3)	N/A

Table 148: Mapping of transformation function (XY) of PSF with next state (N) and readout (R) functions of ZA

PSF		ZA	
XY#	IoX Transformation	N trajectory	Final R
XY-S1	(IoX_S1, IoX_S3)	((S_A2, IoX_A1), S_A1)	(S_A1, IoX_A3)
XY-S2	(IoX_S2, IoX_S4)	((S_A1, IoX_A2), S_A2)	(S_A2, IoX_A4)
XY-S3	(IoX_S5, IoX_S5)	N/A	N/A

A.6.2 ZB definition from PSF

Table 149 provides IoX mapping, Table 150 provides IF mapping, Table 151 provides IoX-IF mapping, and Table 152 provides mapping between XY function of PSF to next state (N) and final readout (R) functions of the SM. From the result, the SM may be defined PSF_S2, PSF_S3, and PSF_4 and may not be defined from PSF_S1, PSF_S5, PSF_S6, or PSF_S7. The result was validated through the DEVS simulations in MS4 Me.

Table 149: Item of exchange (IoX) mapping from PSF to system model ZB

PSF	ZB
IoX_S1	IoX_B1
IoX_S2	IoX_B2
	IoX_B3
	IoX_B4
IoX_S3	IoX_B5
IoX_S4	IoX_B6
	IoX_B7
IoX_S5	N/A

Table 150: Interface (IF) mapping from PSF to system model ZB

PSF	ZB
IF-S1	IF-B1
IF-S2	IF-B2
IF-S3	N/A

Table 151: IoX and IF paired mapping from PSF to system model ZB

PSF	ZB
(IoX_S1, IF-S1)	(IoX_B1, IF-Bl)
(IoX_S2, IF-S1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_S3, IF-S2)	(IoX_B5, IF-B2)
(IoX_S4, IF-S2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
(IoX_S5, IF-S3)	N/A

Table 152: Mapping of transformation function (XY) of PSF with next state (N) and readout (R) functions of ZB

PSF		ZB	
XY#	IoX Transformation	N trajectory	Final R
XY-S1	(IoX_S1, IoX_S3)	((S_B2, IoX_B1), S_B1)	(S_B1, IoX_B5)
		((S_B3, IoX_B4), S_B2), ((S_B2, IoX_B1), S_B1)	(S_B1, IoX_B5)
XY-S2	(IoX_S2, IoX_S4)	((S_B1, IoX_B2), S_B2)	(S_B2, IoX_B6)
		((S_B1, IoX_B2), S_B2), ((S_B2, IoX_B3), S_B3),	(S_B3, IoX_B7)
		((S_B1, IoX_B2), S_B2), ((S_B2, IoX_B3), S_B3), ((S_B3, IoX_B4), S_B2)	(S_B2, IoX_B6)
		((S_B2, IoX_B3), S_B3),	(S_B3, IoX_B7)
		((S_B3, IoX_B4), S_B2)	(S_B2, IoX_B6)
XY-S3	(IoX_S5, IoX_S5)	N/A	N/A

A.6.3 ZC definition from PSF

Table 153 provides IoX mapping, Table 154 provides IF mapping, Table 155 provides IoX-IF mapping, and Table 156 provides mapping between XY function of PSF to next state (N) and final readout (R) functions of the SM. From the result, the SM may be defined only from PSF_S5 and may not be defined from PSF_S1, PSF_S2, PSF_S3, PSF_S4, PSF_S6, or PSF_S7. The result was validated through the DEVS simulations in MS4 Me.

Table 153: Item of exchange (IoX) mapping from PSF to system model ZC

PSF	ZC
IoX_S1	N/A
IoX_S2	N/A
IoX_S3	N/A
IoX_S4	N/A
IoX_S5	IoX_C1

Table 154: Interface (IF) mapping from PSF to system model ZC

PSF	ZC
IF-S1	N/A
IF-S2	N/A
IF-S3	IF-C1

Table 155: IoX and IF paired mapping from PSF to system model ZC

PSF	ZC
(IoX_S1, IF-S1)	N/A
(IoX_S2, IF-S1)	N/A
(IoX_S3, IF-S2)	N/A
(IoX_S4, IF-S2)	N/A
(IoX_S5, IF-S3)	(IoX_C1, IF-C1)

Table 156: Mapping of transformation function (XY) of PSF with next state (N) and readout (R) functions of ZC

PSF		ZC	
XY#	IoX Transformation	N trajectory	Final R
XY-S1	(IoX_S1, IoX_S3)	N/A	N/A
XY-S2	(IoX_S2, IoX_S4)	N/A	N/A
XY-S3	(IoX_S5, IoX_S5)	((S_C1, IoX_C1), S_C1)	(S_C1, IoX_C1)

A.6.4 ZA2 definition from PSF

Table 157 provides IoX mapping, Table 158 provides IF mapping, Table 159 provides IoX-IF mapping, and Table 160 provides mapping between XY function of PSF to next state (N) and final readout (R) functions of the SM. From the result, the SM may be defined PSF_S2, PSF_S3, and PSF_4 and may not be defined from PSF_S1, PSF_S5, PSF_S6, or PSF_S7. The result was validated through the DEVS simulations in MS4 Me.

Table 157: Item of exchange (IoX) mapping from PSF to system model ZA2

PSF	ZA2
IoX_S1	IoX_A1

IoX_S2	IoX_A2
IoX_S3	IoX_A3
IoX_S4	IoX_A4
IoX_S5	N/A

Table 158: Interface (IF) mapping from PSF to system model ZA2

PSF	ZA2
IF-S1	IF-A1
IF-S2	IF-A2
IF-S3	N/A

Table 159: IoX and IF paired mapping from PSF to system model ZA2

PSF	ZA2
(IoX_S1, IF-S1)	(IoX_A1, IF-Al)
(IoX_S2, IF-S1)	(IoX_A2, IF-A1)
(IoX_S3, IF-S2)	(IoX_A3, IF-A2)
(IoX_S4, IF-S2)	(IoX_A4, IF-A2)
(IoX_S5, IF-S3)	N/A

Table 160: Mapping of transformation function (XY) of PSF with next state (N) and readout (R) functions of ZA2

PSF		ZA2	
XY#	IoX Transformation	N trajectory	Final R
XY-S1	(IoX_S1, IoX_S3)	((S_A@2, IoX_A1), S_A@1)	(S_A@1, IoX_A3)
XY-S2	(IoX_S2, IoX_S4)	((S_A@1, IoX_A2), S_A@2)	(S_A@2, IoX_A4)
XY-S3	(IoX_S5, IoX_S5)	N/A	N/A

A.6.5 ZB2 definition from PSF

Table 161 provides IoX mapping, Table 162 provides IF mapping, Table 163 provides IoX-IF mapping, and Table 164 provides mapping between XY function of PSF to next state (N) and final readout (R) functions of the SM. From the result, the SM may be defined PSF_S2, PSF_S3, and PSF_4 and may not be defined from PSF_S1, PSF_S5, PSF_S6, or PSF_S7. The result was validated through the DEVS simulations in MS4 Me.

Table 161: Item of exchange (IoX) mapping from PSF to system model ZB2

PSF	ZB
IoX_S1	IoX_B1
IoX_S2	IoX_B2
	IoX_B3
	IoX_B4

IoX_S3	IoX_B5
IoX_S4	IoX_B6
	IoX_B7
IoX_S5	N/A

Table 162: Interface (IF) mapping from PSF to system model ZB2

PSF	ZB2
IF-S1	IF-B1
IF-S2	IF-B2
IF-S3	N/A

Table 163: IoX and IF paired mapping from PSF to system model ZB2

PSF	ZB2
(IoX_S1, IF-S1)	(IoX_B1, IF-Bl)
(IoX_S2, IF-S1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_S3, IF-S2)	(IoX_B5, IF-B2)
(IoX_S4, IF-S2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
(IoX_S5, IF-S3)	N/A

Table 164: Mapping of transformation function (XY) of PSF with next state (N) and readout (R) functions of ZB2

PSF		ZB2	
XY#	IoX Transformation	N trajectory	Final R
XY-S1	(IoX_S1, IoX_S3)	((S_B@2, IoX_B1), S_B@1)	(S_B@1, IoX_B5)
		((S_B@3, IoX_B4), S_B@2), ((S_B@2, IoX_B1), S_B@1)	(S_B@1, IoX_B5)
XY-S2	(IoX_S2, IoX_S4)	((S_B@1, IoX_B2), S_B@2)	(S_B@2, IoX_B6)
		((S_B@1, IoX_B2), S_B@2), ((S_B@2, IoX_B3), S_B@3),	(S_B@3, IoX_B7)
		((S_B@1, IoX_B2), S_B@2), ((S_B@2, IoX_B3), S_B@3),	(S_B@2, IoX_B6)

		((S_B@3, IoX_B4), S_B@2)	
		((S_B@2, IoX_B3), S_B@3),	(S_B@3, IoX_B7)
		((S_B@3, IoX_B4), S_B@2)	(S_B@2, IoX_B6)
XY-S3	(IoX_S5, IoX_S5)	N/A	N/A

A.6.6 ZAC1 definition from PSF

Table 165 provides IoX mapping, Table 166 provides IF mapping, Table 167 provides IoX-IF mapping, and Table 168 provides mapping between XY function of PSF to next state (N) and final readout (R) functions of the SM. From the result, the SM may be defined from PSF_S1, PSF_S2, PSF_S3, PSF_4, PSF_S5, PSF_S6, or PSF_S7 and there are no PSF that the SM may not be defined from. The result was validated through the DEVS simulations in MS4 Me.

Table 165: Item of exchange (IoX) mapping from PSF to system model ZAC1

PSF	ZAC1
IoX_S1	IoX_A1
IoX_S2	IoX_A2
IoX_S3	IoX_A3
IoX_S4	IoX_A4
IoX_S5	IoX_C1

Table 166: Interface (IF) mapping from PSF to system model ZAC1

PSF	ZAC1
IF-S1	IF-A1
IF-S2	IF-A2
IF-S3	IF-C1

Table 167: IoX and IF paired mapping from PSF to system model ZAC1

PSF	ZAC1
(IoX_S1, IF-S1)	(IoX_A1, IF-Al)
(IoX_S2, IF-S1)	(IoX_A2, IF-A1)
(IoX_S3, IF-S2)	(IoX_A3, IF-A2)
(IoX_S4, IF-S2)	(IoX_A4, IF-A2)
(IoX_S5, IF-S3)	(IoX_C1, IF-C1)

Table 168: Mapping of transformation function (XY) of PSF with next state (N) and readout (R) functions of ZAC1

PSF		ZAC1	
XY#	IoX Transformation	N trajectory	Final R

XY-S1	(IoX_S1, IoX_S3)	((S_AC2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC1, (IoX_A3, IoX_C1))
XY-S2	(IoX_S2, IoX_S4)	((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC2, (IoX_A4, IoX_C1))
XY-S3	(IoX_S5, IoX_S5)	((S_AC2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC1, (IoX_A3, IoX_C1))
		((S_A1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC2, (IoX_A4, IoX_C1))

A.6.7 ZAC2 definition from PSF

Table 169 provides IoX mapping, Table 170 provides IF mapping, Table 171 provides IoX-IF mapping, and Table 172 provides mapping between XY function of PSF to next state (N) and final readout (R) functions of the SM. From the result, the SM may be defined from PSF_S1, PSF_S2, PSF_S3, PSF_4, PSF_S5, PSF_S6, or PSF_S7 and there are no PSF that the SM may not be defined from. The result was validated through the DEVS simulations in MS4 Me.

Table 169: Item of exchange (IoX) mapping from PSF to system model ZAC2

PSF	ZAC2
IoX_S1	IoX_A1
IoX_S2	IoX_A2
IoX_S3	IoX_A3
IoX_S4	IoX_A4
IoX_S5	IoX_C1

Table 170: Interface (IF) mapping from PSF to system model ZAC2

PSF	ZAC2
IF-S1	IF-A1
IF-S2	IF-A2
IF-S3	IF-C1

Table 171: IoX and IF paired mapping from PSF to system model ZAC2

PSF	ZAC2
(IoX_S1, IF-S1)	(IoX_A1, IF-Al)
(IoX_S2, IF-S1)	(IoX_A2, IF-A1)
(IoX_S3, IF-S2)	(IoX_A3, IF-A2)
(IoX_S4, IF-S2)	(IoX_A4, IF-A2)
(IoX_S5, IF-S3)	(IoX_C1, IF-C1)

Table 172: Mapping of transformation function (XY) of PSF with next state (N) and readout (R) functions of ZAC2

PSF	ZAC2

XY#	IoX Transformation	N trajectory	Final R
XY-S1	(IoX_S1, IoX_S3)	((S_AC@2, (IoX_A1, IoX_C1)), S_AC@1)	(S_AC@1, (IoX_A3, IoX_C1))
XY-S2	(IoX_S2, IoX_S4)	((S_AC@1, (IoX_A2, IoX_C1)), S_A@2)	(S_AC@2, (IoX_A4, IoX_C1))
XY-S3	(IoX_S5, IoX_S5)	((S_AC@2, (IoX_A1, IoX_C1)), S_AC@1)	(S_AC@1, (IoX_A3, IoX_C1))
		((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))

A.6.8 ZBC1 definition from PSF

Table 173 provides IoX mapping, Table 174 provides IF mapping, Table 175 provides IoX-IF mapping, and Table 176 provides mapping between XY function of PSF to next state (N) and final readout (R) functions of the SM. From the result, the SM may be defined from PSF_S1, PSF_S2, PSF_S3, PSF_4, PSF_S5, PSF_S6, or PSF_S7 and there are no PSF that the SM may not be defined from. The result was validated through the DEVS simulations in MS4 Me.

Table 173: Item of exchange (IoX) mapping from PSF to system model ZBC1

PSF	ZBC1
IoX_S1	IoX_B1
IoX_S2	IoX_B2
	IoX_B3
	IoX_B4
IoX_S3	IoX_B5
IoX_S4	IoX_B6
	IoX_B7
IoX_S5	IoX_C1

Table 174: Interface (IF) mapping from PSF to system model ZBC1

PSF	ZBC1
IF-S1	IF-B1
IF-S2	IF-B2
IF-S3	IF-C1

Table 175: IoX and IF paired mapping from PSF to system model ZBC1

PSF	ZBC1
(IoX_S1, IF-S1)	(IoX_B1, IF-Bl)
(IoX_S2, IF-S1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_S3, IF-S2)	(IoX_B5, IF-B2)
(IoX_S4, IF-S2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
(IoX_S5, IF-S3)	(IoX_C1, IF-C1)

Table 176: Mapping of transformation function (XY) of PSF with next state (N) and readout (R) functions of ZBC1

PSF		ZBC1	
XY#	IoX Transformation	N trajectory	Final R
XY-S1	(IoX_S1, IoX_S3)	((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))
		((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_B2, IoX_B1), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))
XY-S2	(IoX_S2, IoX_S4)	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))
		((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))
		((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))
		((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))
		((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))
XY-S3	(IoX_S5, IoX_S5)	((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))
		((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_B2, IoX_B1), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))
		((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))

		((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))
		((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))
		((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))
		((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))

A.6.9 ZBC2 definition from PSF

Table 177 provides IoX mapping, Table 178 provides IF mapping, Table 179 provides IoX-IF mapping, and Table 180 provides mapping between XY function of PSF to next state (N) and final readout (R) functions of the SM. From the result, the SM may be defined from PSF_S1, PSF_S2, PSF_S3, PSF_4, PSF_S5, PSF_S6, or PSF_S7 and there are no PSF that the SM may not be defined from. The result was validated through the DEVS simulations in MS4 Me.

Table 177: Item of exchange (IoX) mapping from PSF to system model ZBC2

PSF	ZBC2
IoX_S1	IoX_B1
IoX_S2	IoX_B2
	IoX_B3
	IoX_B4
IoX_S3	IoX_B5
IoX_S4	IoX_B6
	IoX_B7
IoX_S5	IoX_C1

Table 178: Interface (IF) mapping from PSF to system model ZBC2

PSF	ZBC2
IF-S1	IF-B1
IF-S2	IF-B2
IF-S3	IF-C1

Table 179: IoX and IF paired mapping from PSF to system model ZBC2

PSF	ZBC2

(IoX_S1, IF-S1)	(IoX_B1, IF-Bl)
(IoX_S2, IF-S1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_S3, IF-S2)	(IoX_B5, IF-B2)
(IoX_S4, IF-S2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
(IoX_S5, IF-S3)	(IoX_C1, IF-C1)

Table 180: Mapping of transformation function (XY) of PSF with next state (N) and readout (R) functions of ZBC2

PSF		ZBC2	
XY#	IoX Transformation	N trajectory	Final R
XY-S1	(IoX_S1, IoX_S3)	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
		((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, IoX_B1), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
XY-S2	(IoX_S2, IoX_S4)	((S_BC@1, (IoX_B2, IoX_C1)), S_B@2)	(S_BC@2, (IoX_B6, IoX_C1))
		((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
		((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_B@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4,	(S_BC@2, (IoX_B6, IoX_C1))

		IoX_C1)), S_BC@2)	
		((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
		((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
XY-S3	(IoX_S5, IoX_S5)	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
		((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, IoX_B1), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
		((S_BC@1, (IoX_B2, IoX_C1)), S_B@2)	(S_BC@2, (IoX_B6, IoX_C1))
		((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
		((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_B@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
		((S_BC@2, (IoX_B3,	(S_BC@3, (IoX_B7, IoX_C1))

		IoX_C1)), S_BC@3),	
		((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))

A.7 Supporting results of definition of SM from SM

A.7.1 ZAD and ZBD morphism

Table 181 provides IoX mapping, Table 182 provides IF mapping, Table 183 provides IoX-IF mapping, Table 184 provides state mapping, and Table 185 provides mapping between next state (N) and final readout (R) functions of the SM. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, and PSF_S7 because neither SM provide XY-S3 functionality. The result was validated through the DEVS simulations in MS4 Me.

Table 181: Item of exchange (IoX) mapping between system models ZAD and ZBD

ZAD	ZBD
IoX_A1	IoX_B1
IoX_A2	IoX_B2
	IoX_B3
	IoX_B4
IoX_A5	IoX_B8
IoX_A6	IoX_B9
	IoX_B10

Table 182: Interface (IF) mapping between system models ZAD and ZBD

ZAD	ZBD
IF-A1	IF-B1
IF-A3	IF-B3

Table 183: IoX-IF pair mapping between system models ZAD and ZBD

ZAD	ZBD
(IoX_A1, IF-Al)	(IoX_B1, IF-Bl)
(IoX_A2, IF-A1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_A5, IF-A3)	(IoX_B8, IF-B3)
(IoX_A6, IF-A3)	(IoX_B9, IF-B3)
	(IoX_B10, IF-B3)

Table 184: State mapping between system models ZAD and ZBD

ZAD	ZBD
S_AD1	S_BD1
S_AD2	S_BD2
	S_BD3

Table 185: Next state (N) and readout (R) functions mapping between system models ZAD and ZBD

XY Reference	ZAD		ZBD	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AD2, IoX_A1), S_AD1)	(S_AD1, IoX_A5)	((S_BD2, IoX_B1), S_BD1)	(S_BD1, IoX_B8)
			((S_BD3, IoX_B4), S_BD2), ((S_BD2, IoX_B1), S_BD1)	(S_BD1, IoX_B8)
XY-S2	((S_AD1, IoX_A2), S_AD2)	(S_AD2, IoX_A6)	((S_BD1, IoX_B2), S_BD2)	(S_BD2, IoX_B9)
			((S_BD1, IoX_B2), S_BD2), ((S_BD2, IoX_B3), S_BD3),	(S_BD3, IoX_B10)
			((S_BD1, IoX_B2), S_BD2), ((S_BD2, IoX_B3), S_B3), ((S_BD3, IoX_B4), S_BD2)	(S_BD2, IoX_B9)
			((S_BD2, IoX_B3), S_BD3),	(S_BD3, IoX_B10)
			((S_BD3, IoX_B4), S_BD2)	(S_BD2, IoX_B9)
XY-S3	N/A	N/A	N/A	N/A

A.7.2 ZAE and ZBE morphism

Table 186 provides IoX mapping, Table 187 provides IF mapping, Table 188 provides IoX-IF mapping, Table 189 provides state mapping, and Table 190 provides mapping between next state (N) and final readout (R) functions of the SM. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, and PSF_S7 because neither SM provide XY-S3 functionality. The result was validated through the DEVS simulations in MS4 Me.

Table 186: Item of exchange (IoX) mapping between system models ZAE and ZBE

ZAE	ZBE
IoX_A3	IoX_B5
IoX_A4	IoX_B6
	IoX_B7
IoX_A5	IoX_B8
IoX_A6	IoX_B9
	IoX_B10

Table 187: Interface (IF) mapping between system models ZAE and ZBE

ZAE	ZBE
IF-A2	IF-B2
IF-A3	IF-B3

Table 188: IoX-IF pair mapping between system models ZAE and ZBE

ZAE	ZBE
(IoX_A3, IF-A2)	(IoX_B5, IF-B2)
(IoX_A4, IF-A2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
(IoX_A5, IF-A3)	(IoX_B8, IF-B3)
(IoX_A6, IF-A3)	(IoX_B9, IF-B3)
	(IoX_B10, IF-B3)

Table 189: State mapping between system models ZAE and ZBE

ZAE	ZBE
S_AE1	S_BE1
S_AE2	S_BE2
	S_BE3

Table 190: Next state (N) and readout (R) functions mapping between system models ZAE and ZBE

XY Reference	ZAE		ZBE	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AE2, IoX_A5), S_AE1),	(S_AE1, IoX_A3)	((S_BE2, IoX_B8), S_BE1)	(S_BE1, IoX_B5)
			((S_BE3, IoX_B9), S_BE2), ((S_BE2, IoX_B8), S_BE1)	(S_BE1, IoX_B5)
XY-S2	((S_AE1, IoX_A6), S_AE2)	(S_AE2, IoX_A4)	((S_BE1, IoX_B9), S_BE2)	(S_BE2, IoX_B6)
			((S_BE1, IoX_B9), S_BE2), ((S_BE2, IoX_B10), S_B3)	(S_BE3, IoX_B7)
			((S_BE3, IoX_B9), S_BE2)	(S_BE2, IoX_B6)
			((S_BE2, IoX_B10), S_B3)	(S_BE3, IoX_B7)
XY-S3	N/A	N/A	N/A	N/A

A.7.3 ZAC1 and ZA morphism

Table 191 provides IoX mapping, Table 192 provides IF mapping, Table 193 provides IoX-IF mapping, Table 194 provides state mapping, and Table 195 provides mapping between next state (N) and final readout (R) functions of the SM. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. The result was validated through the DEVS simulations in MS4 Me.

Table 191: Item of exchange (IoX) mapping between system models ZAC1 and ZA

ZAC1	ZA
IoX_A1	IoX_A1
IoX_A2	IoX_A2
IoX_A3	IoX_A3
IoX_A4	IoX_A4

IoX_C1	N/A

Table 192: Interface (IF) mapping between system models ZAC1 and ZA

ZAC1	ZA
IF-A1	IF-A1
IF-A2	IF-A2
IF-C1	N/A

Table 193: IoX-IF pair mapping between system models ZAC1 and ZA

ZAC1	ZA
(IoX_A1, IF-Al)	(IoX_A1, IF-Al)
(IoX_A2, IF-A1)	(IoX_A2, IF-A1)
(IoX_A3, IF-A2)	(IoX_A3, IF-A2)
(IoX_A4, IF-A2)	(IoX_A4, IF-A2)
(IoX_C1, IF-C1)	N/A

Table 194: State mapping between system models ZAC1 and ZA

ZAC1	ZA
S_AC1	S_A1
S_AC2	S_A2

Table 195: Next state (N) and readout (R) functions mapping between system models ZAC1 and ZA

XY Reference	ZAC1		ZA	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AC2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC1, (IoX_A3, IoX_C1))	((S_A2, IoX_A1), S_A1)	(S_A1, IoX_A3)
XY-S2	((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC2, (IoX_A4, IoX_C1))	((S_A1, IoX_A2), S_A2)	(S_A2, IoX_A4)
XY-S3	((S_AC2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC1, (IoX_A3, IoX_C1))	N/A	N/A
	((S_A1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC2, (IoX_A4, IoX_C1))		

A.7.4 ZAC1 and ZB morphism

Table 196 provides IoX mapping, Table 197 provides IF mapping, Table 198 provides IoX-IF mapping, Table 199 provides state mapping, and Table 200 provides mapping between next state (N) and final readout (R) functions of the SM. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. The result was validated through the DEVS simulations in MS4 Me.

Table 196: Item of exchange (IoX) mapping between system models ZAC1 and ZB

ZAC1	ZB
IoX_A1	IoX_B1
IoX_A2	IoX_B2
	IoX_B3
	IoX_B4
IoX_A3	IoX_B5
IoX_A4	IoX_B6
	IoX_B7
IoX_C1	N/A

Table 197: Interface (IF) mapping between system models ZAC1 and ZB

ZAC1	ZB
IF-A1	IF-B1
IF-A2	IF-B2
IF-C1	N/A

Table 198: IoX-IF pair mapping between system models ZAC1 and ZB

ZAC1	ZB
(IoX_A1, IF-Al)	(IoX_B1, IF-Bl)
(IoX_A2, IF-A1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_A3, IF-A2)	(IoX_B5, IF-B2)
(IoX_A4, IF-A2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
(IoX_C1, IF-C1)	N/A

Table 199: State mapping between system models ZAC1 and ZB

ZAC1	ZB
S_AC1	S_B1
S_AC2	S_B2

	S_B3

Table 200: Next state (N) and readout (R) functions mapping between system models ZAC1 and ZB

<table>
<tr><th rowspan="2">XY Reference</th><th colspan="2">ZAC1</th><th colspan="2">ZB</th></tr>
<tr><th>N trajectory</th><th>Final R</th><th>N trajectory</th><th>Final R</th></tr>
<tr><td rowspan="2">XY-S1</td><td rowspan="2">((S_AC2, (IoX_A1, IoX_C1)), S_AC1)
((S_AC1, (IoX_A2, IoX_C1)), S_AC2)</td><td rowspan="2">(S_AC1, (IoX_A3, IoX_C1))
(S_AC2, (IoX_A4, IoX_C1))</td><td>((S_B2, IoX_B1), S_B1)</td><td>(S_B1, IoX_B5)</td></tr>
<tr><td>((S_B3, IoX_B4), S_B2), ((S_B2, IoX_B1), S_B1)</td><td>(S_B1, IoX_B5)</td></tr>
<tr><td rowspan="5">XY-S2</td><td rowspan="5">((S_AC2, (IoX_A1, IoX_C1)), S_AC1)
((S_A1, (IoX_A2, IoX_C1)), S_AC2)</td><td rowspan="5">(S_AC1, (IoX_A3, IoX_C1))
(S_AC2, (IoX_A4, IoX_C1))</td><td>((S_B1, IoX_B2), S_B2)</td><td>(S_B2, IoX_B6)</td></tr>
<tr><td>((S_B1, IoX_B2), S_B2), ((S_B2, IoX_B3), S_B3),</td><td>(S_B3, IoX_B7)</td></tr>
<tr><td>((S_B1, IoX_B2), S_B2), ((S_B2, IoX_B3), S_B3), ((S_B3, IoX_B4), S_B2)</td><td>(S_B2, IoX_B6)</td></tr>
<tr><td>((S_B2, IoX_B3), S_B3),</td><td>(S_B3, IoX_B7)</td></tr>
<tr><td>((S_B3, IoX_B4), S_B2)</td><td>(S_B2, IoX_B6)</td></tr>
<tr><td rowspan="2">XY-S3</td><td>((S_AC2, (IoX_A1, IoX_C1)), S_A1)</td><td>(S_AC1, (IoX_A3, IoX_C1))</td><td rowspan="2">N/A</td><td rowspan="2">N/A</td></tr>
<tr><td>((S_AC1, (IoX_A2, IoX_C1)), S_A2)</td><td>(S_AC2, (IoX_A4, IoX_C1))</td></tr>
</table>

A.7.5 ZAC1 and ZC morphism

Table 201 provides IoX mapping, Table 202 provides IF mapping, Table 203 provides IoX-IF mapping, Table 204 provides state mapping, and Table 205 provides mapping between next state (N) and final readout (R) functions of the SM. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S7 only and may be defined as such. and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S2, PSF_S3, PSF_S4, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S1 or XY-S2 functionality. The result was validated through the DEVS simulations in MS4 Me.

Table 201: Item of exchange (IoX) mapping between system models ZAC1 and ZC

ZAC1	ZC
IoX_A1	N/A
IoX_A2	N/A
IoX_A3	N/A
IoX_A4	N/A
IoX_C1	IoX_C1

Table 202: Interface (IF) mapping between system models ZAC1 and ZC

ZAC1	ZC
IF-A1	N/A
IF-A2	N/A
IF-C1	IF-C1

Table 203: IoX-IF pair mapping between system models ZAC1 and ZC

ZAC1	ZC
(IoX_A1, IF-Al)	N/A
(IoX_A2, IF-A1)	N/A
(IoX_A3, IF-A2)	N/A
(IoX_A4, IF-A2)	N/A
(IoX_C1, IF-C1)	(IoX_C1, IF-C1)

Table 204: State mapping between system models ZAC1 and ZC

ZAC1	ZC
S_AC1	S_C1
S_AC2	

Table 205: Next state (N) and readout (R) functions mapping between system models ZAC1 and ZC

<table>
<tr><th rowspan="2">XY Reference</th><th colspan="2">ZAC1</th><th colspan="2">ZC</th></tr>
<tr><th>N trajectory</th><th>Final R</th><th>N trajectory</th><th>Final R</th></tr>
</table>

XY-S1	((S_AC2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC1, (IoX_A3, IoX_C1))	N/A	N/A
XY-S2	((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC2, (IoX_A4, IoX_C1))	N/A	N/A
XY-S3	((S_AC2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC1, (IoX_A3, IoX_C1))	((S_C1, IoX_C1), S_C1)	(S_C1, IoX_C1)
	((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC2, (IoX_A4, IoX_C1))		

A.7.6 ZAC1 and ZA2 morphism

Table 206 provides IoX mapping, Table 207 provides IF mapping, Table 208 provides IoX-IF mapping, Table 209 provides the state mapping, Table 210 provides mapping between next state (N) and final readout (R) functions of the SM, Table 211 provides component mapping, and Table 212 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. Note, because only one SM is specified at L1 and lacks specification of internal coupling structure, there cannot exist morphism at L2. The result was validated through the DEVS simulations in MS4 Me.

Table 206: Item of exchange (IoX) mapping between system models ZAC1 and ZA2

ZAC1	ZA2
IoX_A1	IoX_A1
IoX_A2	IoX_A2
IoX_A3	IoX_A3
IoX_A4	IoX_A4
N/A	IoX_A5
N/A	IoX_A6
IoX_C1	N/A

Table 207: Interface (IF) mapping between system models ZAC1 and ZA2

ZAC1	ZA2
IF-A1	IF-A1
IF-A2	IF-A2

N/A	IF-A3
IF-C1	N/A

Table 208: IoX-IF pair mapping between system models ZAC1 and ZA2

ZAC1	ZA2
(IoX_A1, IF-Al)	(IoX_A1, IF-Al)
(IoX_A2, IF-A1)	(IoX_A2, IF-A1)
(IoX_A3, IF-A2)	(IoX_A3, IF-A2)
(IoX_A4, IF-A2)	(IoX_A4, IF-A2)
N/A	(IoX_A5, IF-A3)
N/A	(IoX_A6, IF-A3)
(IoX_C1, IF-C1)	N/A

Table 209: State mapping between system models ZAC1 and ZA2

ZAC1	ZA2
S_AC1	S_A@1
S_AC2	S_A@2

Table 210: Next state (N) and readout (R) functions mapping between system models ZAC1 and ZA2

XY Reference	ZAC1		ZA2	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AC2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC1, (IoX_A3, IoX_C1))	((S_A@2, IoX_A1), S_A@1)	(S_A@1, IoX_A3)
XY-S2	((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC2, (IoX_A4, IoX_C1))	((S_A@1, IoX_A2), S_A@2)	(S_A@2, IoX_A4)
XY-S3	((S_AC2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC1, (IoX_A3, IoX_C1))	N/A	N/A
	((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC2, (IoX_A4, IoX_C1))		

Table 211: Component mapping between system models ZAC1 and ZA2

ZAC1	ZA2

Components	Components
N/A	ZAD
N/A	ZAE

Table 212: System coupling recipe (SCR) mapping between system models ZAC1 and ZA2

ZAC1	ZA2
SCR	SCR
N/A	((Z_AD, Z_AE), (IoX_A5, IF-A3))
N/A	((Z_AD, Z_AE), (IoX_A6, IF-A3))
N/A	N/A
N/A	N/A

A.7.7 ZAC1 and ZB2 morphism

Table 213 provides IoX mapping, Table 214 provides IF mapping, Table 215 provides IoX-IF mapping, Table 216 provides state mapping, Table 217 provides mapping between next state (N) and final readout (R) functions of the SM, Table 218 provides component mapping, and Table 219 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. Note, because only one SM is specified at L1 and lacks specification of internal coupling structure, there cannot exist morphism at L2. The result was validated through the DEVS simulations in MS4 Me.

Table 213: Item of exchange (IoX) mapping between system models ZAC1 and ZB2

ZAC1	ZB
IoX_A1	IoX_B1
IoX_A2	IoX_B2
	IoX_B3
	IoX_B4
IoX_A3	IoX_B5
IoX_A4	IoX_B6
	IoX_B7
N/A	IoX_B8
N/A	IoX_B9
N/A	IoX_B10
IoX_C1	N/A

Table 214: Interface (IF) mapping between system models ZAC1 and ZB2

ZAC1	ZB
IF-A1	IF-B1
IF-A2	IF-B2

N/A	IF-B3
IF-C1	N/A

Table 215: IoX-IF pair mapping between system models ZAC1 and ZB2

ZAC1	ZB2
(IoX_A1, IF-Al)	(IoX_B1, IF-Bl)
(IoX_A2, IF-A1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_A3, IF-A2)	(IoX_B5, IF-B2)
(IoX_A4, IF-A2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
N/A	(IoX_B8, IF-B3)
N/A	(IoX_B9, IF-B3)
N/A	(IoX_B10, IF-B3)
(IoX_C1, IF-C1)	N/A

Table 216: State mapping between system models ZAC1 and ZB2

ZAC1	ZB2
S_AC1	S_B@1
S_AC2	S_B@2
	S_B@3

Table 217: Next state (N) and readout (R) functions mapping between system models ZAC1 and ZB2

XY Reference	ZAC1		ZB2	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AC2, (IoX_A1, IoX_C1)), S_AC1) ((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC1, (IoX_A3, IoX_C1)) (S_AC2, (IoX_A4, IoX_C1))	((S_B@2, IoX_B1), S_B@1)	(S_B@1, IoX_B5)
			((S_B@3, IoX_B4), S_B@2), ((S_B@2, IoX_B1), S_B@1)	(S_B@1, IoX_B5)
XY-S2	((S_AC2, (IoX_A1, IoX_C1)), S_AC1) ((S_A1, (IoX_A2,	(S_AC1, (IoX_A3, IoX_C1)) (S_AC2, (IoX_A4, IoX_C1))	((S_B@1, IoX_B2), S_B@2)	(S_B@2, IoX_B6)
			((S_B@1, IoX_B2), S_B@2), ((S_B@2,	(S_B@3, IoX_B7)

	IoX_C1)), S_AC2)		IoX_B3), S_B@3),	
			((S_B@1, IoX_B2), S_B@2), ((S_B@2, IoX_B3), S_B3), ((S_B@3, IoX_B4), S_B@2)	(S_B@2, IoX_B6)
			((S_B@2, IoX_B3), S_B@3),	(S_B@3, IoX_B7)
			((S_B@3, IoX_B4), S_B@2)	(S_B@2, IoX_B6)
XY-S3	((S_AC2, (IoX_A1, IoX_C1)), S_A1)	(S_AC1, (IoX_A3, IoX_C1))	N/A	N/A
	((S_AC1, (IoX_A2, IoX_C1)), S_A2)	(S_AC2, (IoX_A4, IoX_C1))		

Table 218: Component mapping between system models ZAC1 and ZB2

ZAC1	ZB2
Components	Components
N/A	ZBD
N/A	ZBE

Table 219: System coupling recipe (SCR) mapping between system models ZAC1 and ZB2

ZAC1	ZB2
SCR	SCR
N/A	((Z_BD, Z_BE), (IoX_B8, IF-B3))
N/A	((Z_BD, Z_BE), (IoX_B9, IF-B3))
N/A	((Z_BD, Z_BE), (IoX_B10, IF-B3))
N/A	((Z_BD, Z_C), Ø)
N/A	((Z_BE, Z_C), Ø)

A.7.8 ZAC1 and ZAC2 morphism

Table 220 provides IoX mapping, Table 221 provides IF mapping, Table 222 provides IoX-IF mapping, Table 223 provides state mapping, Table 224 provides mapping between next state (N) and final readout (R) functions of the SM, Table 225 provides component mapping, and Table 226 provides mapping of component coupling. From the results, between the SM there is an isomorphism at L1 with respect to PSF_S1, PSF_S2, PSF_S3, PSF_S4, PSF_S5, PSF_S6, and PSF_S7 and may be defined as such because all SM provide XY-S1, XY-2, and XY-S3 functionality. Note, because only one SM is specified at L1 and lacks specification of internal coupling structure, there cannot exist morphism at L2. The result was validated through the DEVS simulations in MS4 Me.

Table 220: Item of exchange (IoX) mapping between system models ZAC1 and ZAC2

ZAC1	ZAC2
IoX_A1	IoX_A1
IoX_A2	IoX_A2
IoX_A3	IoX_A3
IoX_A4	IoX_A4
N/A	IoX_A5
N/A	IoX_A6
IoX_C1	IoX_C1

Table 221: Interface (IF) mapping between system models ZAC1 and ZAC2

ZAC1	ZAC2
IF-A1	IF-A1
IF-A2	IF-A2
N/A	IF-A3
IF-C1	IF-C1

Table 222: IoX-IF pair mapping between system models ZAC1 and ZAC2

ZAC1	ZAC2
(IoX_A1, IF-Al)	(IoX_A1, IF-Al)
(IoX_A2, IF-A1)	(IoX_A2, IF-A1)
(IoX_A3, IF-A2)	(IoX_A3, IF-A2)
(IoX_A4, IF-A2)	(IoX_A4, IF-A2)
N/A	(IoX_A5, IF-A3)
N/A	(IoX_A6, IF-A3)
(IoX_C1, IF-C1)	(IoX_C1, IF-C1)

Table 223: State mapping between system models ZAC1 and ZAC2

ZAC1	ZAC2
S_AC1	S_AC@1

S_AC2	S_AC@2

Table 224: Next state (N) and readout (R) functions mapping between system models ZAC1 and ZAC2

XY Reference	ZAC1		ZAC2	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AC2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC1, (IoX_A3, IoX_C1))	((S_AC@2, IoX_A1), S_A@1)	(S_AC@1, IoX_A3)
XY-S2	((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC2, (IoX_A4, IoX_C1))	((S_AC@1, IoX_A2), S_A@2)	(S_AC@2, IoX_A4)
XY-S3	((S_AC2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC1, (IoX_A3, IoX_C1))	((S_AC@2, (IoX_A1, IoX_C1)), S_AC@1)	(S_AC@1, (IoX_A3, IoX_C1))
	((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC2, (IoX_A4, IoX_C1))	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))

Table 225: Component mapping between system models ZAC1 and ZAC2

ZAC1	ZAC2
Components	Components
N/A	ZAD
N/A	ZAE
N/A	ZC

Table 226: System coupling recipe (SCR) mapping between system models ZAC1 and ZAC2

ZAC1	ZAC2
SCR	SCR
N/A	((Z_AD, Z_AE), (IoX_A5, IF-A3))
N/A	((Z_AD, Z_AE), (IoX_A6, IF-A3))
N/A	((Z_AD, Z_C), Ø)
N/A	((Z_AE, Z_C), Ø)

A.7.9 ZAC1 and ZBC1 morphism

Table 227 provides IoX mapping, Table 228 provides IF mapping, Table 229 provides state mapping, Table 230 provides IoX-IF mapping, and Table 231 provides mapping between next state (N) and final readout (R) functions of the SM. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S1, PSF_S2, PSF_S3, PSF_S4, PSF_S5, PSF_S6, and PSF_S7 and may be defined as such because all SM provide XY-S1, XY-2, and XY-S3 functionality. The result was validated through the DEVS simulations in MS4 Me.

Table 227: Item of exchange (IoX) mapping between system models ZAC1 and ZBC1

ZAC1	ZBC1
IoX_A1	IoX_B1
IoX_A2	IoX_B2
	IoX_B3
	IoX_B4
IoX_A3	IoX_B5
IoX_A4	IoX_B6
	IoX_B7
IoX_C1	IoX_C1

Table 228: Interface (IF) mapping between system models ZAC1 and ZBC1

ZAC1	ZBC1
IF-A1	IF-B1
IF-A2	IF-B2
IF-C1	IF-C1

Table 229: IoX-IF pair mapping between system models ZAC1 and ZBC1

ZAC1	ZBC1
(IoX_A1, IF-Al)	(IoX_B1, IF-Bl)
(IoX_A2, IF-A1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_A3, IF-A2)	(IoX_B5, IF-B2)
(IoX_A4, IF-A2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
(IoX_C1, IF-C1)	(IoX_C1, IF-C1)

Table 230: State mapping between system models ZAC1 and ZBC1

ZAC1	ZBBC1
S_AC1	S_BC1
S_AC2	S_BC2
	S_BC3

Table 231: Next state (N) and readout (R) functions mapping between system models ZAC1 and ZBC1

XY Reference	ZAC1		ZBC1	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AC2, (IoX_A1, IoX_C1)), S_AC1) ((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC1, (IoX_A3, IoX_C1)) (S_AC2, (IoX_A4, IoX_C1))	((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))
			((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))
XY-S2	((S_AC2, (IoX_A1, IoX_C1)), S_AC1) ((S_A1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC1, (IoX_A3, IoX_C1)) (S_AC2, (IoX_A4, IoX_C1))	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))
			((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))
			((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))
			((S_BC2, IoX_B3), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))
			((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))

XY-S3	((S_AC2, (IoX_A1, IoX_C1)), S_A1) ((S_AC1, (IoX_A2, IoX_C1)), S_A2)	(S_AC1, (IoX_A3, IoX_C1)) (S_AC2, (IoX_A4, IoX_C1))	((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))
			((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))
	((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC2, (IoX_A4, IoX_C1))	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))
			((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))
			((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))
			((S_BC2, IoX_B3), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))
			((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))

A.7.10 ZAC1 and ZBC2 morphism

Table 232 provides IoX mapping, Table 233 provides IF mapping, Table 234 provides IoX-IF mapping, Table 235 provides state mapping, Table 236 provides mapping between next state (N) and final readout (R) functions of the SM, Table 237 provides component mapping, and Table 238 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S1, PSF_S2, PSF_S3, PSF_S4, PSF_S5, PSF_S6, and PSF_S7 and may be defined as such because all SM provide XY-S1, XY-2, and XY-S3 functionality. Note, because only one SM is specified at L1 and lacks specification of internal coupling structure, there cannot exist morphism at L2. The result was validated through the DEVS simulations in MS4 Me.

Table 232: Item of exchange (IoX) mapping between system models ZAC1 and ZBC2

ZAC1	ZBC2
IoX_A1	IoX_B1
IoX_A2	IoX_B2
	IoX_B3
	IoX_B4
IoX_A3	IoX_B5
IoX_A4	IoX_B6
	IoX_B7
N/A	IoX_B8
N/A	IoX_B9
N/A	IoX_B10
IoX_C1	IoX_C1

Table 233: Interface (IF) mapping between system models ZAC1 and ZBC2

ZAC1	ZBC2
IF-A1	IF-B1
IF-A2	IF-B2
IF-C1	IF-C1

Table 234: IoX-IF pair mapping between system models ZAC1 and ZBC2

ZAC1	ZBC2
(IoX_A1, IF-Al)	(IoX_B1, IF-Bl)
(IoX_A2, IF-A1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_A3, IF-A2)	(IoX_B5, IF-B2)
(IoX_A4, IF-A2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
N/A	(IoX_B8, IF-B3)
N/A	(IoX_B9, IF-B3)

N/A	(IoX_B10, IF-B3)
(IoX_C1, IF-C1)	(IoX_C1, IF-C1)

Table 235: State mapping between system models ZAC1 and ZBC2

ZAC1	ZBC2
S_AC1	S_BC@1
S_AC2	S_BC@2
	S_BC@3

Table 236: Next state (N) and readout (R) functions mapping between system models ZAC1 and ZBC2

XY Reference	ZAC1		ZBC2	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AC2, (IoX_A1, IoX_C1)), S_AC1) ((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC1, (IoX_A3, IoX_C1)) (S_AC2, (IoX_A4, IoX_C1))	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
			((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
XY-S2	((S_AC2, (IoX_A1, IoX_C1)), S_AC1) ((S_A1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC1, (IoX_A3, IoX_C1)) (S_AC2, (IoX_A4, IoX_C1))	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
			((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
			((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@2, (IoX_B6, IoX_C1))

			((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	
			((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
			((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
XY-S3	((S_AC2, (IoX_A1, IoX_C1)), S_A1) ((S_AC1, (IoX_A2, IoX_C1)), S_A2)	(S_AC1, (IoX_A3, IoX_C1)) (S_AC2, (IoX_A4, IoX_C1))	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
			((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
	((S_AC1, (IoX_A2, IoX_C1)), S_AC2)	(S_AC2, (IoX_A4, IoX_C1))	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
			((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
			((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4,	(S_BC@2, (IoX_B6, IoX_C1))

			IoX_C1)), S_BC@2)	
			((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
			((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))

Table 237: Component mapping between system models ZAC1 and ZBC2

ZAC1	ZBC2
Components	Components
N/A	ZBD
N/A	ZBE
N/A	ZC

Table 238: System coupling recipe (SCR) mapping between system models ZAC1 and ZBC2

ZAC1	ZBC2
SCR	SCR
N/A	((Z_BD, Z_BE), (IoX_B8, IF-B3))
N/A	((Z_BD, Z_BE), (IoX_B9, IF-B3))
N/A	((Z_BD, Z_BE), (IoX_B10, IF-B3))
N/A	((Z_BD, Z_C), Ø)
N/A	((Z_BE, Z_C), Ø)

A.7.11 ZAC2 and ZA morphism

Table 239 provides IoX mapping, Table 240 provides IF mapping, Table 241 provides IoX-IF mapping, Table 242 provides state mapping, Table 243 provides mapping between next state (N) and final readout (R) functions of the SM, Table 244 provides component mapping, and Table 245 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. Note, because only one SM is specified at L1 and lacks specification of internal coupling structure, there cannot exist morphism at L2. The result was validated through the DEVS simulations in MS4 Me.

Table 239: Item of exchange (IoX) mapping between system models ZAC2 and ZA

ZAC2	ZA
IoX_A1	IoX_A1

IoX_A2	IoX_A2
IoX_A3	IoX_A3
IoX_A4	IoX_A4
IoX_A5	N/A
IoX_A6	N/A
IoX_C1	N/A

Table 240: Interface (IF) mapping between system models ZAC2 and ZA

ZAC2	ZA
IF-A1	IF-A1
IF-A2	IF-A2
IF-A3	N/A
IF-C1	N/A

Table 241: IoX-IF pair mapping between system models ZAC2 and ZA

ZAC2	ZA
(IoX_A1, IF-Al)	(IoX_A1, IF-Al)
(IoX_A2, IF-A1)	(IoX_A2, IF-A1)
(IoX_A3, IF-A2)	(IoX_A3, IF-A2)
(IoX_A4, IF-A2)	(IoX_A4, IF-A2)
(IoX_A5, IF-A3)	N/A
(IoX_A6, IF-A3)	N/A
(IoX_C1, IF-C1)	N/A

Table 242: State mapping between system models ZAC2 and ZA

ZAC2	ZA
S_AC@1	S_A1
S_AC@2	S_A2

Table 243: Next state (N) and readout (R) functions mapping between system models ZAC2 and ZA

XY Reference	ZAC2		ZA	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AC@2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC@1, (IoX_A3, IoX_C1))	((S_A2, IoX_A1), S_A1)	(S_A1, IoX_A3)
XY-S2	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))	((S_A1, IoX_A2), S_A2)	(S_A2, IoX_A4)

XY-S3	((S_AC@2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC@1, (IoX_A3, IoX_C1))	N/A	N/A
	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))		

Table 244: Component mapping between system models ZAC2 and ZA

ZAC2	ZA
Components	Components
ZAD	N/A
ZAE	N/A
ZC	N/A

Table 245: System coupling recipe (SCR) mapping between system models ZAC2 and ZA

ZAC2	ZA
SCR	SCR
((Z_AD, Z_AE), (IoX_A5, IF-A3))	N/A
((Z_AD, Z_AE), (IoX_A6, IF-A3))	N/A
((Z_AD, Z_C), Ø)	N/A
((Z_AE, Z_C), Ø)	N/A

A.7.12 ZAC2 and ZB morphism

Table 246 provides IoX mapping, Table 247 provides IF mapping, Table 248 provides IoX-IF mapping, Table 249 provides state mapping, Table 250 provides mapping between next state (N) and final readout (R) functions of the SM, Table 251 provides component mapping, and Table 252 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. Note, because only one SM is specified at L1 and lacks specification of internal coupling structure, there cannot exist morphism at L2. The result was validated through the DEVS simulations in MS4 Me.

Table 246: Item of exchange (IoX) mapping between system models ZAC2 and ZB

ZAC2	ZB
IoX_A1	IoX_B1
IoX_A2	IoX_B2
	IoX_B3
	IoX_B4

IoX_A3	IoX_B5
IoX_A4	IoX_B6
	IoX_B7
IoX_A5	N/A
IoX_A6	N/A
IoX_C1	N/A

Table 247: Interface (IF) mapping between system models ZAC2 and ZB

ZAC1	ZB
IF-A1	IF-B1
IF-A2	IF-B2
IF-A3	N/A
IF-C1	N/A

Table 248: IoX-IF pair) mapping between system models ZAC2 and ZB

ZAC1	ZB
(IoX_A1, IF-Al)	(IoX_B1, IF-Bl)
(IoX_A2, IF-A1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_A3, IF-A2)	(IoX_B5, IF-B2)
(IoX_A4, IF-A2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
(IoX_A5, IF-A3)	N/A
(IoX_A6, IF-A3)	N/A
(IoX_C1, IF-C1)	N/A

Table 249: State mapping between system models ZAC2 and ZB

ZAC1	ZB
S_AC@1	S_B1
S_AC@2	S_B2
	S_B3

Table 250: Next state (N) and readout (R) functions mapping between system models ZAC2 and ZB

<table>
<tr><th rowspan="2">XY Reference</th><th colspan="2">ZAC1</th><th colspan="2">ZB</th></tr>
<tr><th>N trajectory</th><th>Final R</th><th>N trajectory</th><th>Final R</th></tr>
<tr><td rowspan="2">XY-S1</td><td rowspan="2">((S_AC@2, (IoX_A1, IoX_C1)), S_AC@1)</td><td rowspan="2">(S_AC@1, (IoX_A3, IoX_C1))</td><td>((S_B2, IoX_B1), S_B1)</td><td>(S_B1, IoX_B5)</td></tr>
<tr><td>((S_B3, IoX_B4),</td><td>(S_B1, IoX_B5)</td></tr>
</table>

			S_B2), ((S_B2, IoX_B1), S_B1)	
XY-S2	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))	((S_B1, IoX_B2), S_B2)	(S_B2, IoX_B6)
			((S_B1, IoX_B2), S_B2), ((S_B2, IoX_B3), S_B3),	(S_B3, IoX_B7)
			((S_B1, IoX_B2), S_B2), ((S_B2, IoX_B3), S_B3), ((S_B3, IoX_B4), S_B2)	(S_B2, IoX_B6)
			((S_B2, IoX_B3), S_B3),	(S_B3, IoX_B7)
			((S_B3, IoX_B4), S_B2)	(S_B2, IoX_B6)
XY-S3	((S_AC@2, (IoX_A1, IoX_C1)), S_AC@1)	(S_AC@1, (IoX_A3, IoX_C1))	N/A	N/A
	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))		

Table 251: Component mapping between system models ZAC2 and ZB

ZAC2	ZB
Components	Components
ZAD	N/A
ZAE	N/A
ZC	N/A

Table 252: System coupling recipe (SCR) mapping between system models ZAC2 and ZB

ZAC2	ZB
SCR	SCR
((Z_AD, Z_AE), (IoX_A5, IF-A3))	N/A
((Z_AD, Z_AE), (IoX_A6, IF-A3))	N/A
((Z_AD, Z_C), Ø)	N/A
((Z_AE, Z_C), Ø)	N/A

A.7.13 ZAC2 and ZC morphism

Table 253 provides IoX mapping, Table 254 provides IF mapping, Table 255 provides IoX-IF mapping, Table 256 provides state mapping, Table 257 provides mapping between next state (N) and final readout (R) functions of the SM, Table 258 provides component mapping, and Table 259 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S7 only and may be defined as such. and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S2, PSF_S3, PSF_S4, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S1 or XY-S2 functionality. Note, because only one SM is specified at L1 and lacks specification of internal coupling structure, there cannot exist morphism at L2. The result was validated through the DEVS simulations in MS4 Me.

Table 253: Item of exchange (IoX) mapping between system models ZAC2 and ZC

ZAC2	ZC
IoX_A1	N/A
IoX_A2	N/A
IoX_A3	N/A
IoX_A4	N/A
IoX_A5	N/A
IoX_A6	N/A
IoX_C1	IoX_C1

Table 254: Interface (IF) mapping between system models ZAC2 and ZC

ZAC2	ZC
IF-A1	N/A
IF-A2	N/A
IF-A3	N/A
IF-C1	IF-C1

Table 255: IoX-IF pair mapping between system models ZAC2 and ZC

ZAC2	ZC
(IoX_A1, IF-Al)	N/A
(IoX_A2, IF-A1)	N/A
(IoX_A3, IF-A2)	N/A

(IoX_A4, IF-A2)	N/A
(IoX_A5, IF-A3)	N/A
(IoX_A6, IF-A3)	N/A
(IoX_C1, IF-C1)	(IoX_C1, IF-C1)

Table 256: State mapping between system models ZAC2 and ZC

ZAC2	ZC
S_AC@1	S_C1
S_AC@2	

Table 257: Next state (N) and readout (R) functions mapping between system models ZAC2 and ZC

XY Reference	ZAC2		ZC	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AC@2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC@1, (IoX_A3, IoX_C1))	N/A	N/A
XY-S2	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))	N/A	N/A
XY-S3	((S_AC@2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC@1, (IoX_A3, IoX_C1))	((S_C1, IoX_C1), S_C1)	(S_C1, IoX_C1)
	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))		

Table 258: Component mapping between system models ZAC2 and ZC

ZAC2	ZC
Components	Components
ZAD	N/A
ZAE	N/A
ZC	N/A

Table 259: System coupling recipe (SCR) mapping between system models ZAC2 and ZC

ZAC2	ZC
SCR	SCR
((Z_AD, Z_AE), (IoX_A5, IF-A3))	N/A
((Z_AD, Z_AE), (IoX_A6, IF-A3))	N/A
((Z_AD, Z_C), Ø)	N/A
((Z_AE, Z_C), Ø)	N/A

A.7.14 ZAC2 and ZA2 morphism

Table 260 provides IoX mapping, Table 261 provides IF mapping, Table 262 provides IoX-IF mapping, Table 263 provides state mapping, Table 264 provides mapping between next state (N) and final readout (R) functions of the SM, Table 265 provides component mapping, and Table 266 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L2 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. This is supported by the component morphisms proven in previous sections. Note, because both of the SM are specified at L2, the homomorphism exists at both L2 as well as L1 by proof of L2 morphism. The result was validated through the DEVS simulations in MS4 Me.

Table 260: Item of exchange (IoX) mapping between system models ZAC2 and ZA2

ZAC2	ZA2
IoX_A1	IoX_A1
IoX_A2	IoX_A2
IoX_A3	IoX_A3
IoX_A4	IoX_A4
IoX_A5	IoX_A5
IoX_A6	IoX_A6
IoX_C1	N/A

Table 261: Interface (IF) mapping between system models ZAC2 and ZA2

ZAC2	ZA2
IF-A1	IF-A1
IF-A2	IF-A2
IF-A3	IF-A3
IF-C1	N/A

Table 262: IoX-IF pair mapping between system models ZAC2 and ZA2

ZAC2	ZA2
(IoX_A1, IF-Al)	(IoX_A1, IF-Al)
(IoX_A2, IF-A1)	(IoX_A2, IF-A1)

(IoX_A3, IF-A2)	(IoX_A3, IF-A2)
(IoX_A4, IF-A2)	(IoX_A4, IF-A2)
(IoX_A5, IF-A3)	(IoX_A5, IF-A3)
(IoX_A6, IF-A3)	(IoX_A6, IF-A3)
(IoX_C1, IF-C1)	N/A

Table 263: State mapping between system models ZAC2 and ZA2

ZAC2	ZA2
S_AC@1	S_A1
S_AC@2	S_A2

Table 264: Next state (N) and readout (R) functions mapping between system models ZAC2 and ZA2

XY Reference	ZAC2		ZA2	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AC@2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC@1, (IoX_A3, IoX_C1))	((S_A@2, IoX_A1), S_A@1)	(S_A@1, IoX_A3)
XY-S2	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))	((S_A@1, IoX_A2), S_A@2)	(S_A@2, IoX_A4)
XY-S3	((S_AC@2, (IoX_A1, IoX_C1)), S_AC1)	(S_AC@1, (IoX_A3, IoX_C1))	N/A	N/A
	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))		

Table 265: Component mapping between system models ZAC2 and ZA2

ZAC2	ZA2
Components	Components
ZAD	ZAD
ZAE	ZAE
ZC	N/A

Table 266: System coupling recipe (SCR) mapping between system models ZAC2 and ZA2

ZAC2	ZA2
SCR	SCR
((Z_AD, Z_AE), (IoX_A5, IF-A3))	((Z_AD, Z_AE), (IoX_A5, IF-A3))
((Z_AD, Z_AE), (IoX_A6, IF-A3))	((Z_AD, Z_AE), (IoX_A6, IF-A3))
((Z_AD, Z_C), Ø)	N/A
((Z_AE, Z_C), Ø)	N/A

A.7.15 ZAC2 and ZB2 morphism

Table 267 provides IoX mapping, Table 268 provides IF mapping, Table 269 provides IoX-IF mapping, Table 270 provides state mapping, Table 271 provides mapping between next state (N) and final readout (R) functions of the SM, Table 272 provides component mapping, and Table 273 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L2 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. This is supported by the component morphisms proven in previous sections. Note, because both of the SM are specified at L2, the homomorphism exists at both L2 as well as L1 by proof of L2 morphism. The result was validated through the DEVS simulations in MS4 Me.

Table 267: Item of exchange (IoX) mapping between system models ZAC2 and ZB2

ZAC2	ZB2
IoX_A1	IoX_B1
IoX_A2	IoX_B2
	IoX_B3
	IoX_B4
IoX_A3	IoX_B5
IoX_A4	IoX_B6
	IoX_B7
IoX_A5	IoX_B8
IoX_A6	IoX_B9
	IoX_B10
IoX_C1	N/A

Table 268: Interface (IF) mapping between system models ZAC2 and ZB2

ZAC1	ZB2
IF-A1	IF-B1
IF-A2	IF-B2
IF-A3	IF-B3
IF-C1	N/A

Table 269: IoX-IF pair mapping between system models ZAC2 and ZB2

ZAC1	ZB2
(IoX_A1, IF-Al)	(IoX_B1, IF-Bl)
(IoX_A2, IF-A1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_A3, IF-A2)	(IoX_B5, IF-B2)
(IoX_A4, IF-A2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
(IoX_A5, IF-A3)	(IoX_B8, IF-B3)
(IoX_A6, IF-A3)	(IoX_B9, IF-B3)
	(IoX_B10, IF-B3)
(IoX_C1, IF-C1)	N/A

Table 270: State mapping between system models ZAC2 and ZB2

ZAC1	ZB2
S_AC@1	S_B@1
S_AC@2	S_B@2
	S_B@3

Table 271: Next state (N) and readout (R) functions mapping between system models ZAC2 and ZB2

XY Reference	ZAC1		ZB2	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AC@2, (IoX_A1, IoX_C1)), S_AC@1)	(S_AC@1, (IoX_A3, IoX_C1))	((S_B@2, IoX_B1), S_B@1)	(S_B@1, IoX_B5)
			((S_B@3, IoX_B4), S_B@2), ((S_B@2, IoX_B1), S_B@1)	(S_B@1, IoX_B5)
XY-S2	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))	((S_B@1, IoX_B2), S_B@2)	(S_B@2, IoX_B6)
			((S_B@1, IoX_B2), S_B@2), ((S_B@2, IoX_B3), S_B@3),	(S_B@3, IoX_B7)
			((S_B@1, IoX_B2),	(S_B@2, IoX_B6)

			S_B@2), ((S_B@2, IoX_B3), S_B3), ((S_B@3, IoX_B4), S_B@2)	
			((S_B@2, IoX_B3), S_B@3),	(S_B@3, IoX_B7)
			((S_B@3, IoX_B4), S_B@2)	(S_B@2, IoX_B6)
XY-S3	((S_AC@2, (IoX_A1, IoX_C1)), S_AC@1)	(S_AC@1, (IoX_A3, IoX_C1))	N/A	N/A
	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))		

Table 272: Component mapping between system models ZAC2 and ZB2

ZAC2	ZB2
Components	Components
ZAD	ZBD
ZAE	ZBE
ZC	N/A

Table 273: System coupling recipe (SCR) mapping between system models ZAC2 and ZB2

ZAC2	ZB2
SCR	SCR
((Z_AD, Z_AE), (IoX_A5, IF-A3))	((Z_BD, Z_BE), (IoX_B8, IF-B3))
((Z_AD, Z_AE), (IoX_A6, IF-A3))	((Z_BD, Z_BE), (IoX_B9, IF-B3))
	((Z_BD, Z_BE), (IoX_B10, IF-B3))
((Z_AD, Z_C), Ø)	((Z_BD, Z_C), Ø)
((Z_AE, Z_C), Ø)	((Z_BE, Z_C), Ø)

A.7.16 ZAC2 and ZBC1 morphism

Table 274 provides IoX mapping, Table 275 provides IF mapping, Table 276 provides IoX-IF mapping, Table 277 provides state mapping, Table 278 provides mapping between next state (N) and final readout (R) functions of the SM, Table 279 provides component mapping, and Table 280 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S1, PSF_S2, PSF_S3, PSF_S4, PSF_S5, PSF_S6, and PSF_S7 and may be defined as such because all SM provide XY-S1, XY-2, and XY-S3 functionality. Note, because only one SM is specified at L1 and lacks specification of internal coupling structure, there cannot exist morphism at L2. The result was validated through the DEVS simulations in MS4 Me.

Table 274: Item of exchange (IoX) mapping between system models ZAC2 and ZBC1

ZAC2	ZBC1
IoX_A1	IoX_B1
IoX_A2	IoX_B2
	IoX_B3
	IoX_B4
IoX_A3	IoX_B5
IoX_A4	IoX_B6
	IoX_B7
IoX_A5	N/A
IoX_A6	N/A
	N/A
IoX_C1	IoX_C1

Table 275: Interface (IF) mapping between system models ZAC2 and ZBC1

ZAC1	ZBC1
IF-A1	IF-B1
IF-A2	IF-B2
IF-A3	N/A
IF-C1	IF-C1

Table 276: IoX-IF pair mapping between system models ZAC2 and ZBC1

ZAC1	ZBC1
(IoX_A1, IF-Al)	(IoX_B1, IF-Bl)
(IoX_A2, IF-A1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_A3, IF-A2)	(IoX_B5, IF-B2)
(IoX_A4, IF-A2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
(IoX_A5, IF-A3)	N/A
(IoX_A6, IF-A3)	N/A
	(IoX_B10, IF-B3)
(IoX_C1, IF-C1)	(IoX_C1, IF-C1)

Table 277: State mapping between system models ZAC2 and ZBC1

<table>
<tr><th>ZAC1</th><th>ZBC1</th></tr>
<tr><td>S_AC@1</td><td>S_BC1</td></tr>
<tr><td rowspan="2">S_AC@2</td><td>S_BC2</td></tr>
<tr><td>S_BC3</td></tr>
</table>

Table 278: Next state (N) and readout (R) functions mapping between system models ZAC2 and ZBC1

<table>
<tr><th rowspan="2">XY Reference</th><th colspan="2">ZAC1</th><th colspan="2">ZBC1</th></tr>
<tr><th>N trajectory</th><th>Final R</th><th>N trajectory</th><th>Final R</th></tr>
<tr><td rowspan="2">XY-S1</td><td rowspan="2">((S_AC@2, (IoX_A1, IoX_C1)), S_AC@1)</td><td rowspan="2">(S_AC@1, (IoX_A3, IoX_C1))</td><td>((S_BC2, (IoX_B1, IoX_C1)), S_BC1)</td><td>(S_BC1, (IoX_B5, IoX_C1))</td></tr>
<tr><td>((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)</td><td>(S_BC1, (IoX_B5, IoX_C1))</td></tr>
<tr><td rowspan="3">XY-S2</td><td rowspan="3">((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)</td><td rowspan="3">(S_AC@2, (IoX_A4, IoX_C1))</td><td>((S_BC1, (IoX_B2, IoX_C1)), S_BC2)</td><td>(S_BC2, (IoX_B6, IoX_C1))</td></tr>
<tr><td>((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),</td><td>(S_BC3, (IoX_B7, IoX_C1))</td></tr>
<tr><td>((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4,</td><td>(S_BC2, (IoX_B6, IoX_C1))</td></tr>
</table>

			IoX_C1)), S_BC2)	
			((S_BC2, IoX_B3), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))
			((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))
XY-S3	((S_AC@2, (IoX_A1, IoX_C1)), S_AC@1)	(S_AC@1, (IoX_A3, IoX_C1))	((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))
			((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))
	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))
			((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))
			((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))

			((S_BC2, IoX_B3), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))
			((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))

Table 279: Component mapping between system models ZAC2 and ZBC1

ZAC2	ZBC1
Components	Components
ZAD	N/A
ZAE	N/A
ZC	N/A

Table 280: System coupling recipe (SCR) mapping between system models ZAC2 and ZBC1

ZAC2	ZBC1
SCR	SCR
((Z_AD, Z_AE), (IoX_A5, IF-A3))	N/A
((Z_AD, Z_AE), (IoX_A6, IF-A3))	N/A
	N/A
((Z_AD, Z_C), Ø)	N/A
((Z_AE, Z_C), Ø)	N/A

A.7.17 ZAC2 and ZBC2 morphism

Table 281 provides IoX mapping, Table 282 provides IF mapping, Table 283 provides IoX-IF mapping, Table 284 provides state mapping, Table 285 provides mapping between next state (N) and final readout (R) functions of the SM, Table 286 provides component mapping, and Table 287 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S1, PSF_S2, PSF_S3, PSF_S4, PSF_S5, PSF_S6, and PSF_S7 and may be defined as such because all SM provide XY-S1, XY-2, and XY-S3 functionality. This is supported by the component morphisms proven in previous sections. Note, because both of the SM are specified at L2, the homomorphism exists at both L2 as well as L1 by proof of L2 morphism. The result was validated through the DEVS simulations in MS4 Me.

Table 281: Item of exchange (IoX) mapping between system models ZAC2 and ZBC2

ZAC2	ZBC2
IoX_A1	IoX_B1
IoX_A2	IoX_B2
	IoX_B3
	IoX_B4

IoX_A3	IoX_B5
IoX_A4	IoX_B6
	IoX_B7
IoX_A5	IoX_B8
IoX_A6	IoX_B9
	IoX_B10
IoX_C1	IoX_C1

Table 282: Interface (IF) mapping between system models ZAC2 and ZBC2

ZAC1	ZBC2
IF-A1	IF-B1
IF-A2	IF-B2
IF-A3	IF-B3
IF-C1	IF-C1

Table 283: IoX-IF pair mapping between system models ZAC2 and ZBC2

ZAC1	ZBC2
(IoX_A1, IF-Al)	(IoX_B1, IF-Bl)
(IoX_A2, IF-A1)	(IoX_B2, IF-B1)
	(IoX_B3, IF-B1)
	(IoX_B4, IF-B1)
(IoX_A3, IF-A2)	(IoX_B5, IF-B2)
(IoX_A4, IF-A2)	(IoX_B6, IF-B2)
	(IoX_B7, IF-B2)
(IoX_A5, IF-A3)	(IoX_B8, IF-B3)
(IoX_A6, IF-A3)	(IoX_B9, IF-B3)
	(IoX_B10, IF-B3)
(IoX_C1, IF-C1)	(IoX_C1, IF-C1)

Table 284: State mapping between system models ZAC2 and ZBC2

ZAC1	ZBC2
S_AC@1	S_B@1
S_AC@2	S_B@2
	S_B@3

Table 285: Next state (N) and readout (R) functions mapping between system models ZAC2 and ZBC2

XY Reference	ZAC1		ZBC2	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_AC@2, (IoX_A1,	(S_AC@1, (IoX_A3, IoX_C1))	((S_BC@2, (IoX_B1,	(S_BC@1, (IoX_B5, IoX_C1))

	IoX_C1)), S_AC@1)		IoX_C1)), S_BC@1)	
			((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
XY-S2	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
			((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
			((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
			((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
			((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
XY-S3	((S_AC@2, (IoX_A1, IoX_C1)), S_AC@1)	(S_AC@1, (IoX_A3, IoX_C1))	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))

			((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
	((S_AC@1, (IoX_A2, IoX_C1)), S_AC@2)	(S_AC@2, (IoX_A4, IoX_C1))	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
			((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
			((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
			((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
			((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))

Table 286: Component mapping between system models ZAC2 and ZBC2

ZAC2	ZBC2
Components	Components
ZAD	ZBD
ZAE	ZBE
ZC	ZC

Table 287: System coupling recipe (SCR) mapping between system models ZAC2 and ZBC2

ZAC2	ZBC2
SCR	SCR
((Z_AD, Z_AE), (IoX_A5, IF-A3))	((Z_BD, Z_BE), (IoX_B8, IF-B3))
((Z_AD, Z_AE), (IoX_A6, IF-A3))	((Z_BD, Z_BE), (IoX_B9, IF-B3))
	((Z_BD, Z_BE), (IoX_B10, IF-B3))
((Z_AD, Z_C), Ø)	((Z_BD, Z_C), Ø)
((Z_AE, Z_C), Ø)	((Z_BE, Z_C), Ø)

A.7.18 ZBC1 and ZA morphism

Table 288 provides IoX mapping, Table 289 provides IF mapping, Table 290 provides IoX-IF mapping, Table 291 provides state mapping, and Table 292 provides mapping between next state (N) and final readout (R) functions of the SM. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. The result was validated through the DEVS simulations in MS4 Me.

Table 288: Item of exchange (IoX) mapping between system models ZBC1 and ZA

ZBC1	ZA
IoX_B1	IoX_A1
IoX_B2	IoX_A2
IoX_B3	
IoX_B4	
IoX_B5	IoX_A3
IoX_B6	IoX_A4
IoX_B7	
IoX_C1	N/A

Table 289: Interface (IF) mapping between system models ZBC1 and ZA

ZBC1	ZA
IF-B1	IF-A1
IF-B2	IF-A2
IF-C1	N/A

Table 290: IoX-IF pair mapping between system models ZBC1 and ZA

ZBC1	ZA
(IoX_B1, IF-Bl)	(IoX_A1, IF-Al)
(IoX_B2, IF-B1)	(IoX_A2, IF-A1)
(IoX_B3, IF-B1)	
(IoX_B4, IF-B1)	
(IoX_B5, IF-B2)	(IoX_A3, IF-A2)
(IoX_B6, IF-B2)	(IoX_A4, IF-A2)
(IoX_B7, IF-B2)	
(IoX_C1, IF-C1)	N/A

Table 291: State mapping between system models ZBC1 and ZA

ZBC1	ZA
S_BC1	S_A1
S_BC2	S_A2
S_BC3	

Table 292: Next state (N) and readout (R) functions mapping between system models ZBC1 and ZA

XY Reference	ZBC1		ZA	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))	((S_A2, IoX_A1), S_A1)	(S_A1, IoX_A3)
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))		
XY-S2	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_A1, IoX_A2), S_A2)	(S_A2, IoX_A4)
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2),	(S_BC3, (IoX_B7, IoX_C1))		

	((S_BC2, (IoX_B3, IoX_C1)), S_BC3),			
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC2, (IoX_B3, IoX_C1)), S_BC3)	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
XY-S3	((S_BC2, (IoX_B1, IoX_C1)), S_BC1) ((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1)) (S_BC1, (IoX_B5, IoX_C1))	N/A	N/A
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		

	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC2, (IoX_B3, IoX_C1)), S_BC3)	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		

A.7.19 ZBC1 and ZB morphism

Table 293 provides IoX mapping, Table 294 provides IF mapping, Table 295 provides IoX-IF mapping, Table 296 provides state mapping, and Table 297 provides mapping between next state (N) and final readout (R) functions of the SM. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. The result was validated through the DEVS simulations in MS4 Me.

Table 293: Item of exchange (IoX) mapping between system models ZBC1 and ZB

ZBC1	ZB
IoX_B1	(IoX_B1, IF-Bl)
IoX_B2	(IoX_B2, IF-B1)
IoX_B3	(IoX_B3, IF-B1)
IoX_B4	(IoX_B4, IF-B1)
IoX_B5	(IoX_B5, IF-B2)

IoX_B6	(IoX_B6, IF-B2)
IoX_B7	(IoX_B7, IF-B2)
N/A	N/A
N/A	N/A
N/A	N/A
IoX_C1	N/A

Table 294: Interface (IF) mapping between system models ZBC1 and ZB

ZBC1	ZB
IF-B1	IF-B1
IF-B2	IF-B2
IF-C1	N/A

Table 295: IoX-IF pair mapping between system models ZBC1 and ZB

ZBC1	ZB
(IoX_B1, IF-Bl)	(IoX_B1, IF-Bl)
(IoX_B2, IF-B1)	(IoX_B2, IF-B1)
(IoX_B3, IF-B1)	(IoX_B3, IF-B1)
(IoX_B4, IF-B1)	(IoX_B4, IF-B1)
(IoX_B5, IF-B2)	(IoX_B5, IF-B2)
(IoX_B6, IF-B2)	(IoX_B6, IF-B2)
(IoX_B7, IF-B2)	(IoX_B7, IF-B2)
N/A	N/A
N/A	N/A
N/A	N/A
(IoX_C1, IF-C1)	N/A

Table 296: State mapping between system models ZBC1 and ZB

ZBC1	ZB
S_BC1	S_B1
S_BC2	S_B2
S_BC3	S_B3

Table 297: Next state (N) and readout (R) functions mapping between system models ZBC1 and ZB

XY Reference	ZBC1		ZB	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))	((S_B2, IoX_B1), S_B1)	(S_B1, IoX_B5)

	((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))	((S_B3, IoX_B4), S_B2), ((S_B2, IoX_B1), S_B1)	(S_B1, IoX_B5)
XY-S2	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_B1, IoX_B2), S_B2)	(S_B2, IoX_B6)
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))	((S_B1, IoX_B2), S_B2), ((S_B2, IoX_B3), S_B3),	(S_B3, IoX_B7)
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_B1, IoX_B2), S_B2), ((S_B2, IoX_B3), S_B3), ((S_B3, IoX_B4), S_B2)	(S_B2, IoX_B6)
	((S_BC2, (IoX_B3, IoX_C1)), S_BC3)	(S_BC3, (IoX_B7, IoX_C1))	((S_B2, IoX_B3), S_B3),	(S_B3, IoX_B7)
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_B3, IoX_B4), S_B2)	(S_B2, IoX_B6)
XY-S3	((S_BC2, (IoX_B1, IoX_C1)), S_BC1) ((S_BC3, (IoX_B4,	(S_BC1, (IoX_B5, IoX_C1)) (S_BC1, (IoX_B5, IoX_C1))	N/A	N/A

	IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)			
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC2, (IoX_B3, IoX_C1)), S_BC3)	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		

A.7.20 ZBC1 and ZC morphism

Table 298 provides IoX mapping, Table 299 provides IF mapping, Table 300 provides IoX-IF mapping, Table 301 provides state mapping, and Table 302 provides mapping between next state (N) and final readout (R) functions of the SM. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S7 only and may be defined as such. and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S2, PSF_S3, PSF_S4, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S1 or XY-S2 functionality. The result was validated through the DEVS simulations in MS4 Me

Table 298: Item of exchange (IoX) mapping between system models ZBC1 and ZC

ZBC1	ZC
IoX_B1	N/A
IoX_B2	N/A
IoX_B3	N/A
IoX_B4	N/A
IoX_B5	N/A
IoX_B6	N/A
IoX_B7	N/A
N/A	N/A
N/A	N/A
N/A	N/A
IoX_C1	IoX_C1

Table 299: Interface (IF) mapping between system models ZBC1 and ZC

ZBC1	ZC
IF-B1	N/A
IF-B2	N/A
N/A	N/A
IF-C1	IF-C1

Table 300: IoX-IF pair mapping between system models ZBC1 and ZC

ZBC1	ZC
(IoX_B1, IF-Bl)	N/A
(IoX_B2, IF-B1)	N/A
(IoX_B3, IF-B1)	N/A
(IoX_B4, IF-B1)	N/A
(IoX_B5, IF-B2)	N/A
(IoX_B6, IF-B2)	N/A
(IoX_B7, IF-B2)	N/A
N/A	N/A
N/A	N/A

N/A	N/A
(IoX_C1, IF-C1)	(IoX_C1, IF-C1)

Table 301: State mapping between system models ZBC1 and ZC

ZBC1	ZC
S_BC1	S_C1
S_BC2	
S_BC3	

Table 302: Next state (N) and readout (R) functions mapping between system models ZBC1 and ZC

XY Reference	ZBC1		ZC	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))	N/A	N/A
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))		
XY-S2	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	N/A	N/A
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC2, (IoX_B6, IoX_C1))		

	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)			
	((S_BC2, (IoX_B3, IoX_C1)), S_BC3)	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
XY-S3	((S_BC2, (IoX_B1, IoX_C1)), S_BC1) ((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1)) (S_BC1, (IoX_B5, IoX_C1))	((S_C1, IoX_C1), S_C1)	(S_C1, IoX_C1)
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3,	(S_BC2, (IoX_B6, IoX_C1))		

	IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)			
	((S_BC2, (IoX_B3, IoX_C1)), S_BC3)	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		

A.7.21 ZBC1 and ZA2 morphism

Table 303 provides IoX mapping, Table 304 provides IF mapping, Table 305 provides IoX-IF mapping, Table 306 provides state mapping, Table 307 provides mapping between next state (N) and final readout (R) functions of the SM, Table 308 provides component mapping, and Table 309 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. The result was validated through the DEVS simulations in MS4 Me.

Table 303: Item of exchange (IoX) mapping between system models ZBC1 and ZA2

ZBC1	ZA2
IoX_B1	IoX_A1
IoX_B2	IoX_A2
IoX_B3	
IoX_B4	
IoX_B5	IoX_A3
IoX_B6	IoX_A4
IoX_B7	
N/A	IoX_A5
N/A	IoX_A6
N/A	
IoX_C1	N/A

Table 304: Interface (IF) mapping between system models ZBC1 and ZA2

ZBC1	ZA2
IF-B1	IF-A1
IF-B2	IF-A2

N/A	IF-A3
IF-C1	N/A

Table 305: IoX-IF pair mapping between system models ZBC1 and ZA2

ZBC1	ZA2
(IoX_B1, IF-Bl)	(IoX_A1, IF-Al)
(IoX_B2, IF-B1)	(IoX_A2, IF-A1)
(IoX_B3, IF-B1)	
(IoX_B4, IF-B1)	
(IoX_B5, IF-B2)	(IoX_A3, IF-A2)
(IoX_B6, IF-B2)	(IoX_A4, IF-A2)
(IoX_B7, IF-B2)	
N/A	(IoX_A5, IF-A3)
N/A	(IoX_A6, IF-A3)
N/A	
(IoX_C1, IF-C1)	N/A

Table 306: State mapping between system models ZBC1 and ZA2

ZBC1	ZA2
S_BC1	S_A@1
S_BC2	S_A@2
S_BC3	

Table 307: Next state (N) and readout (R) functions mapping between system models ZBC1 and ZA2

XY Reference	ZBC1		ZA2	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))	((S_A@2, IoX_A1), S_A@1)	(S_A@1, IoX_A3)
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))		
XY-S2	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_A@1, IoX_A2), S_A@2)	(S_A@2, IoX_A4)

	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC2, (IoX_B3, IoX_C1)), S_BC3)	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
XY-S3	((S_BC2, (IoX_B1, IoX_C1)), S_BC1) ((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1)) (S_BC1, (IoX_B5, IoX_C1))	N/A	N/A
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		

	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC2, (IoX_B3, IoX_C1)), S_BC3)	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		

Table 308: Component mapping between system models ZBC1 and ZA2

ZBC1	ZA2
Components	Components
N/A	ZAD
N/A	ZAE
N/A	N/A

Table 309: System coupling recipe (SCR) mapping between system models ZBC1 and ZA2

ZBC1	ZA2
SCR	SCR
N/A	N/A
N/A	N/A
N/A	N/A
N/A	N/A
N/A	N/A

A.7.22 ZBC1 and ZB2 morphism

Table 310 provides IoX mapping, Table 311 provides IF mapping, Table 312 provides IoX-IF mapping, Table 313 provides state mapping, Table 314 provides mapping between next state (N) and final readout (R) functions of the SM, Table 315 provides component mapping, and Table 316 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. The result was validated through the DEVS simulations in MS4 Me.

Table 310: Item of exchange (IoX) mapping between system models ZBC1 and ZB2

ZBC1	ZB2
IoX_B1	IoX_B1
IoX_B2	IoX_B2
IoX_B3	IoX_B3
IoX_B4	IoX_B4
IoX_B5	IoX_B5
IoX_B6	IoX_B6
IoX_B7	IoX_B7
N/A	IoX_B8
N/A	IoX_B9
N/A	IoX_B10
IoX_C1	N/A

Table 311: Interface (IF) mapping between system models ZBC1 and ZB2

ZBC1	ZB2
IF-B1	IF-B1
IF-B2	IF-B2
N/A	IF-B3
IF-C1	N/A

Table 312: IoX-IF pair mapping between system models ZBC1 and ZB2

ZBC1	ZB2
(IoX_B1, IF-Bl)	(IoX_B1, IF-Bl)
(IoX_B2, IF-B1)	(IoX_B2, IF-B1)
(IoX_B3, IF-B1)	(IoX_B3, IF-B1)
(IoX_B4, IF-B1)	(IoX_B4, IF-B1)
(IoX_B5, IF-B2)	(IoX_B5, IF-B2)
(IoX_B6, IF-B2)	(IoX_B6, IF-B2)
(IoX_B7, IF-B2)	(IoX_B7, IF-B2)
N/A	(IoX_B8, IF-B3)
N/A	(IoX_B9, IF-B3)
N/A	(IoX_B10, IF-B3)
(IoX_C1, IF-C1)	N/A

Table 313: State mapping between system models ZBC1 and ZB2

ZBC1	ZB2
S_BC1	S_B@1
S_BC2	S_B@2
S_BC3	S_B@3

Table 314: Next state (N) and readout (R) functions mapping between system models ZBC1 and ZB2

XY Reference	ZBC1		ZB2	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))	((S_B@2, IoX_B1), S_B@1)	(S_B@1, IoX_B5)
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))	((S_B@3, IoX_B4), S_B@2), ((S_B@2, IoX_B1), S_B@1)	(S_B@1, IoX_B5)
XY-S2	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_B@1, IoX_B2), S_B@2)	(S_B@2, IoX_B6)
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2),	(S_BC3, (IoX_B7, IoX_C1))	((S_B@1, IoX_B2), S_B@2), ((S_B@2,	(S_B@3, IoX_B7)

	((S_BC2, (IoX_B3, IoX_C1)), S_BC3),		IoX_B3), S_B@3),	
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_B@1, IoX_B2), S_B@2), ((S_B@2, IoX_B3), S_B3), ((S_B@3, IoX_B4), S_B@2)	(S_B@2, IoX_B6)
	((S_BC2, (IoX_B3, IoX_C1)), S_BC3)	(S_BC3, (IoX_B7, IoX_C1))	((S_B@2, IoX_B3), S_B@3),	(S_B@3, IoX_B7)
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_B@3, IoX_B4), S_B@2)	(S_B@2, IoX_B6)
XY-S3	((S_BC2, (IoX_B1, IoX_C1)), S_BC1) ((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1)) (S_BC1, (IoX_B5, IoX_C1))	N/A	N/A
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		

	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		
	((S_BC2, (IoX_B3, IoX_C1)), S_BC3)	(S_BC3, (IoX_B7, IoX_C1))		
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))		

Table 315: Component mapping between system models ZBC1 and ZB2

ZBC1	ZB2
Components	Components
N/A	ZBD
N/A	ZBE
N/A	N/A

Table 316: System coupling recipe (SCR) mapping between system models ZBC1 and ZB2

ZBC1	ZB2
SCR	SCR
N/A	((Z_BD, Z_BE), (IoX_B8, IF-B3))
N/A	((Z_BD, Z_BE), (IoX_B9, IF-B3))
N/A	((Z_BD, Z_BE), (IoX_B10, IF-B3))
N/A	((Z_BD, Z_C), Ø)
N/A	((Z_BE, Z_C), Ø)

A.7.23 ZBC1 and ZBC2 morphism

Table 317 provides IoX mapping, Table 318 provides IF mapping, Table 319 provides IoX-IF mapping, Table 320 provides state mapping, Table 321 provides mapping between next state (N) and final readout (R) functions of the SM, Table 322 provides component mapping, and Table 323 provides mapping of component coupling. From the results, between the SM there is an isomorphism at L1 with respect to PSF_S1, PSF_S2, PSF_S3, PSF_S4, PSF_S5, PSF_S6, and PSF_S7 and may be defined as such because all SM provide XY-S1, XY-2, and XY-S3 functionality. Note, because only one SM is specified at L1 and lacks specification of internal coupling structure, there cannot exist morphism at L2. The result was validated through the DEVS simulations in MS4 Me.

Table 317: Item of exchange (IoX) mapping between system models ZBC1 and ZBC2

ZBC1	ZBC2
IoX_B1	IoX_B1
IoX_B2	IoX_B2
IoX_B3	IoX_B3
IoX_B4	IoX_B4
IoX_B5	IoX_B5
IoX_B6	IoX_B6
IoX_B7	IoX_B7
N/A	IoX_B8
N/A	IoX_B9
N/A	IoX_B10
IoX_C1	IoX_C1

Table 318: Interface (IF) mapping between system models ZBC1 and ZBC2

ZBC1	ZBC2
IF-B1	IF-B1
IF-B2	IF-B2
N/A	IF-B3
IF-C1	IF-C1

Table 319: IoX-IF pair mapping between system models ZBC1 and ZBC2

ZBC1	ZBC2
(IoX_B1, IF-Bl)	(IoX_B1, IF-Bl)
(IoX_B2, IF-B1)	(IoX_B2, IF-B1)
(IoX_B3, IF-B1)	(IoX_B3, IF-B1)
(IoX_B4, IF-B1)	(IoX_B4, IF-B1)
(IoX_B5, IF-B2)	(IoX_B5, IF-B2)
(IoX_B6, IF-B2)	(IoX_B6, IF-B2)
(IoX_B7, IF-B2)	(IoX_B7, IF-B2)
N/A	(IoX_B8, IF-B3)

N/A	(IoX_B9, IF-B3)
N/A	(IoX_B10, IF-B3)
(IoX_C1, IF-C1)	(IoX_C1, IF-C1)

Table 320: State mapping between system models ZBC1 and ZBC2

ZBC1	ZBC2
S_BC1	S_B@1
S_BC2	S_B@2
S_BC3	S_B@3

Table 321: Next state (N) and readout (R) functions mapping between system models ZBC1 and ZBC2

XY Reference	ZBC1		ZBC2	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1))	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
XY-S2	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)),	(S_BC2, (IoX_B6, IoX_C1))	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)),	(S_BC@2, (IoX_B6, IoX_C1))

	S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)		S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	
	((S_BC2, (IoX_B3, IoX_C1)), S_BC3)	(S_BC3, (IoX_B7, IoX_C1))	((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
XY-S3	((S_BC2, (IoX_B1, IoX_C1)), S_BC1) ((S_BC3, (IoX_B4, IoX_C1)), S_BC2), ((S_BC2, (IoX_B1, IoX_C1)), S_BC1)	(S_BC1, (IoX_B5, IoX_C1)) (S_BC1, (IoX_B5, IoX_C1))	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3),	(S_BC3, (IoX_B7, IoX_C1))	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))

	((S_BC1, (IoX_B2, IoX_C1)), S_BC2), ((S_BC2, (IoX_B3, IoX_C1)), S_BC3), ((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))
	((S_BC2, (IoX_B3, IoX_C1)), S_BC3)	(S_BC3, (IoX_B7, IoX_C1))	((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))
	((S_BC3, (IoX_B4, IoX_C1)), S_BC2)	(S_BC2, (IoX_B6, IoX_C1))	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))

Table 322: Component mapping between system models ZBC1 and ZBC2

ZBC1	ZBC2
Components	Components
N/A	ZBD
N/A	ZBE
N/A	ZC

Table 323: System coupling recipe (SCR)mapping between system models ZBC1 and ZBC2

ZBC1	ZBC2
SCR	SCR
N/A	((Z_BD, Z_BE), (IoX_B8, IF-B3))
N/A	((Z_BD, Z_BE), (IoX_B9, IF-B3))
N/A	((Z_BD, Z_BE), (IoX_B10, IF-B3))
N/A	((Z_BD, Z_C), Ø)
N/A	((Z_BE, Z_C), Ø)

A.7.24 ZBC2 and ZA morphism

Table 324 provides IoX mapping, Table 325 provides IF mapping, Table 326 provides IoX-IF mapping, Table 327 provides state mapping, Table 328 provides mapping between next state (N) and final readout (R) functions of the SM, Table 329 provides component mapping, and Table 330 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. Note, because only one SM is specified at L1 and lacks specification of internal coupling structure, there cannot exist morphism at L2. The result was validated through the DEVS simulations in MS4 Me.

Table 324: Interface (IF) mapping between system models ZBC2 and ZA

ZBC2	ZA
IoX_B1	IoX_A1
IoX_B2	IoX_A2
IoX_B3	
IoX_B4	
IoX_B5	IoX_A3
IoX_B6	IoX_A4
IoX_B7	
IoX_B8	N/A
IoX_B9	N/A
IoX_B10	N/A
IoX_C1	N/A

Table 325: Item of exchange (IoX) mapping between system models ZBC2 and ZA

ZBC2	ZA
IF-B1	IF-A1
IF-B2	IF-A2
IF-B3	N/A
IF-C1	N/A

Table 326: IoX-IF pair mapping between system models ZBC2 and ZA

ZBC2	ZA
(IoX_B1, IF-Bl)	(IoX_A1, IF-Al)
(IoX_B2, IF-B1)	(IoX_A2, IF-A1)
(IoX_B3, IF-B1)	
(IoX_B4, IF-B1)	
(IoX_B5, IF-B2)	(IoX_A3, IF-A2)
(IoX_B6, IF-B2)	(IoX_A4, IF-A2)
(IoX_B7, IF-B2)	
(IoX_B8, IF-B3)	N/A
(IoX_B9, IF-B3)	N/A
(IoX_B10, IF-B3)	N/A
(IoX_C1, IF-C1)	N/A

Table 327: State mapping between system models ZBC2 and ZA

ZBC2	ZA
S_B@1	S_A1
S_B@2	S_A2
S_B@3	

Table 328: Next state (N) and readout (R) functions mapping between system models ZBC2 and ZA

XY Reference	ZBC2		ZA	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))	((S_A2, IoX_A1), S_A1)	(S_A1, IoX_A3)
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))		
XY-S2	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))	((S_A1, IoX_A2), S_A2)	(S_A2, IoX_A4)
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4,	(S_BC@2, (IoX_B6, IoX_C1))		

	IoX_C1)), S_BC@2)			
	((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		
XY-S3	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))	N/A	N/A
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		

	((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		

Table 329: Component mapping between system models ZBC2 and ZA

ZBC2	ZA
Components	Components
ZBD	N/A
ZBE	N/A
ZC	N/A

Table 330: System coupling recipe (SCR)mapping between system models ZBC2 and ZA

ZBC2	ZA
SCR	SCR
((Z_BD, Z_BE), (IoX_B8, IF-B3))	N/A
((Z_BD, Z_BE), (IoX_B9, IF-B3))	N/A
((Z_BD, Z_BE), (IoX_B10, IF-B3))	N/A
((Z_BD, Z_C), Ø)	N/A
((Z_BE, Z_C), Ø)	N/A

A.7.25 ZBC2 and ZB morphism

Table 331 provides IoX mapping, Table 332 provides IF mapping, Table 333 provides IoX-IF mapping, Table 334 provides state mapping, Table 335 provides mapping between next state (N) and final readout (R) functions of the SM, Table 336 provides component mapping, and Table 337 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. Note, because only one SM is specified at L1 and lacks specification of internal coupling structure, there cannot exist morphism at L2. The result was validated through the DEVS simulations in MS4 Me.

Table 331: Interface (IF) mapping between system models ZBC2 and ZB

ZBC2	ZB
IoX_B1	(IoX_B1, IF-Bl)
IoX_B2	(IoX_B2, IF-B1)
IoX_B3	(IoX_B3, IF-B1)
IoX_B4	(IoX_B4, IF-B1)

IoX_B5	(IoX_B5, IF-B2)
IoX_B6	(IoX_B6, IF-B2)
IoX_B7	(IoX_B7, IF-B2)
IoX_B8	N/A
IoX_B9	N/A
IoX_B10	N/A
IoX_C1	N/A

Table 332: Item of exchange (IoX) mapping between system models ZBC2 and ZB

ZBC2	ZB
IF-B1	IF-B1
IF-B2	IF-B2
IF-B3	N/A
IF-C1	N/A

Table 333: IoX-IF pair mapping between system models ZBC2 and ZB

ZBC2	ZB
(IoX_B1, IF-Bl)	(IoX_B1, IF-Bl)
(IoX_B2, IF-B1)	(IoX_B2, IF-B1)
(IoX_B3, IF-B1)	(IoX_B3, IF-B1)
(IoX_B4, IF-B1)	(IoX_B4, IF-B1)
(IoX_B5, IF-B2)	(IoX_B5, IF-B2)
(IoX_B6, IF-B2)	(IoX_B6, IF-B2)
(IoX_B7, IF-B2)	(IoX_B7, IF-B2)
(IoX_B8, IF-B3)	N/A
(IoX_B9, IF-B3)	N/A
(IoX_B10, IF-B3)	N/A
(IoX_C1, IF-C1)	N/A

Table 334: State mapping between system models ZBC2 and ZB

ZBC2	ZB
S_B@1	S_B1
S_B@2	S_B2
S_B@3	S_B3

Table 335: Next state (N) and readout (R) functions mapping between system models ZBC2 and ZB

XY Reference	ZBC2		ZB	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_BC@2, (IoX_B1,	(S_BC@1, (IoX_B5, IoX_C1))	((S_B2, IoX_B1), S_B1)	(S_B1, IoX_B5)

	IoX_C1)), S_BC@1)			
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))	((S_B3, IoX_B4), S_B2), ((S_B2, IoX_B1), S_B1)	(S_B1, IoX_B5)
XY-S2	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))	((S_B1, IoX_B2), S_B2)	(S_B2, IoX_B6)
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))	((S_B1, IoX_B2), S_B2), ((S_B2, IoX_B3), S_B3),	(S_B3, IoX_B7)
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))	((S_B1, IoX_B2), S_B2), ((S_B2, IoX_B3), S_B3), ((S_B3, IoX_B4), S_B2)	(S_B2, IoX_B6)
	((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))	((S_B2, IoX_B3), S_B3),	(S_B3, IoX_B7)
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))	((S_B3, IoX_B4), S_B2)	(S_B2, IoX_B6)
XY-S3	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))	N/A	N/A

	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		
	((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		

Table 336: Component mapping between system models ZBC2 and ZB

ZBC2	ZB
Components	Components
ZBD	N/A
ZBE	N/A
ZC	N/A

Table 337: System coupling recipe (SCR) mapping between system models ZBC2 and ZB

ZBC2	ZB
SCR	SCR
((Z_BD, Z_BE), (IoX_B8, IF-B3))	N/A
((Z_BD, Z_BE), (IoX_B9, IF-B3))	N/A
((Z_BD, Z_BE), (IoX_B10, IF-B3))	N/A
((Z_BD, Z_C), Ø)	N/A
((Z_BE, Z_C), Ø)	N/A

A.7.26 ZBC2 and ZC morphism

Table 338 provides IoX mapping, Table 339 provides IF mapping, Table 340 provides IoX-IF mapping, Table 341 provides state mapping, Table 342 provides mapping between next state (N) and final readout (R) functions of the SM, Table 343 provides component mapping, and Table 344 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L1 with respect to PSF_S7 only and may be defined as such. and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S2, PSF_S3, PSF_S4, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S1 or XY-S2 functionality. Note, because only one SM is specified at L1 and lacks specification of internal coupling structure, there cannot exist morphism at L2. The result was validated through the DEVS simulations in MS4 Me.

Table 338: Item of exchange (IoX) mapping between system models ZBC2 and ZC

ZBC2	ZC
IoX_B1	N/A
IoX_B2	N/A
IoX_B3	N/A
IoX_B4	N/A
IoX_B5	N/A
IoX_B6	N/A
IoX_B7	N/A
IoX_B8	N/A
IoX_B9	N/A
IoX_B10	N/A
IoX_C1	IoX_C1

Table 339: Interface (IF) mapping between system models ZBC2 and ZC

ZBC2	ZC
IF-B1	N/A
IF-B2	N/A
IF-B3	N/A
IF-C1	IF-C1

Table 340: IoX-IF pair mapping between system models ZBC2 and ZC

ZBC2	ZC
(IoX_B1, IF-Bl)	N/A
(IoX_B2, IF-B1)	N/A
(IoX_B3, IF-B1)	N/A
(IoX_B4, IF-B1)	N/A
(IoX_B5, IF-B2)	N/A
(IoX_B6, IF-B2)	N/A
(IoX_B7, IF-B2)	N/A
(IoX_B8, IF-B3)	N/A
(IoX_B9, IF-B3)	N/A
(IoX_B10, IF-B3)	N/A
(IoX_C1, IF-C1)	(IoX_C1, IF-C1)

Table 341: State mapping between system models ZBC2 and ZC

ZBC2	ZC
S_B@1	S_C1
S_B@2	
S_B@3	

Table 342: Next state (N) and readout (R) functions mapping between system models ZBC2 and ZC

XY Reference	ZBC2		ZC	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))	N/A	N/A
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))		

XY-S2	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))	N/A	N/A
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		
	((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		
XY-S3	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))	((S_C1, IoX_C1), S_C1)	(S_C1, IoX_C1)
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))		
	((S_BC@1, (IoX_B2,	(S_BC@2, (IoX_B6, IoX_C1))		

	IoX_C1)), S_BC@2)			
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		
	((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		

Table 343: Component mapping between system models ZBC2 and ZC

ZBC2	ZC
Components	Components
ZBD	N/A
ZBE	N/A
ZC	N/A

Table 344: System coupling recipe (SCR)mapping between system models ZBC2 and ZC

ZBC2	ZC
SCR	SCR
((Z_BD, Z_BE), (IoX_B8, IF-B3))	N/A
((Z_BD, Z_BE), (IoX_B9, IF-B3))	N/A
((Z_BD, Z_BE), (IoX_B10, IF-B3))	N/A

((Z_BD, Z_C), Ø)	N/A
((Z_BE, Z_C), Ø)	N/A

A.7.27 ZBC2 and ZA2 morphism

Table 345 provides IoX mapping, Table 346 provides IF mapping, Table 347 provides IoX-IF mapping, Table 348 provides state mapping, Table 349 provides mapping between next state (N) and final readout (R) functions of the SM, Table 350 provides component mapping, and Table 351 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L2 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. This is supported by the component morphisms proven in previous sections. Note, because both of the SM are specified at L2, the homomorphism exists at both L2 as well as L1 by proof of L2 morphism. The result was validated through the DEVS simulations in MS4 Me.

Table 345: Item of exchange (IoX) mapping between system models ZBC2 and ZA2

ZBC2	ZA2
IoX_B1	IoX_A1
IoX_B2	IoX_A2
IoX_B3	
IoX_B4	
IoX_B5	IoX_A3
IoX_B6	IoX_A4
IoX_B7	
IoX_B8	IoX_A5
IoX_B9	IoX_A6
IoX_B10	
IoX_C1	N/A

Table 346: Interface (IF) mapping between system models ZBC2 and ZA2

ZBC2	ZA2
IF-B1	IF-A1
IF-B2	IF-A2
IF-B3	IF-A3
IF-C1	N/A

Table 347: IoX-IF pair mapping between system models ZBC2 and ZA2

ZBC2	ZA2
(IoX_B1, IF-Bl)	(IoX_A1, IF-Al)
(IoX_B2, IF-B1)	(IoX_A2, IF-A1)
(IoX_B3, IF-B1)	

(IoX_B4, IF-B1)	
(IoX_B5, IF-B2)	(IoX_A3, IF-A2)
(IoX_B6, IF-B2)	(IoX_A4, IF-A2)
(IoX_B7, IF-B2)	
(IoX_B8, IF-B3)	(IoX_A5, IF-A3)
(IoX_B9, IF-B3)	(IoX_A6, IF-A3)
(IoX_B10, IF-B3)	
(IoX_C1, IF-C1)	N/A

Table 348: State mapping between system models ZBC2 and ZA2

ZBC2	ZA2
S_B@1	S_A@1
S_B@2	S_A@2
S_B@3	

Table 349: Next state (N) and readout (R) functions mapping between system models ZBC2 and ZA2

XY Reference	ZBC2		ZA2	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))	((S_A@2, IoX_A1), S_A@1)	(S_A@1, IoX_A3)
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))		
XY-S2	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))	((S_A@1, IoX_A2), S_A@2)	(S_A@2, IoX_A4)
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		

	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		
	((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		
XY-S3	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))	N/A	N/A
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)),	(S_BC@2, (IoX_B6, IoX_C1))		

	S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)			
	((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		

Table 350: Component mapping between system models ZBC2 and ZA2

ZBC2	ZA2
Components	Components
ZBD	ZAD
ZBE	ZAE
ZC	N/A

Table 351: System coupling recipe (SCR)mapping between system models ZBC2 and ZA2

ZBC2	ZA2
SCR	SCR
((Z_BD, Z_BE), (IoX_B8, IF-B3))	N/A
((Z_BD, Z_BE), (IoX_B9, IF-B3))	N/A
((Z_BD, Z_BE), (IoX_B10, IF-B3))	N/A
((Z_BD, Z_C), Ø)	N/A
((Z_BE, Z_C), Ø)	N/A

A.7.28 ZBC2 and ZB2 morphism

Table 352 provides IoX mapping, Table 353 provides IF mapping, Table 354 provides IoX-IF mapping, Table 355 provides state mapping, Table 356 provides mapping between next state (N) and final readout (R) functions of the SM, Table 357 provides component mapping, and Table 358 provides mapping of component coupling. From the results, between the SM there is a homomorphism at L2 with respect to PSF_S2, PSF_S3, and PSF_S4 and may be defined as such. The SM may not be defined from each other with respect to PSF_S1, PSF_S5, PSF_S6, or PSF_S7 because one SM does not provide XY-S3 functionality. This is supported by the component morphisms proven in previous sections. Note, because both of the SM are specified at L2, the homomorphism exists at both L2 as well as L1 by proof of L2 morphism. The result was validated through the DEVS simulations in MS4 Me.

Table 352: Item of exchange (IoX) mapping between system models ZBC2 and ZB2

ZBC2	ZB2
IoX_B1	IoX_B1
IoX_B2	IoX_B2
IoX_B3	IoX_B3
IoX_B4	IoX_B4
IoX_B5	IoX_B5
IoX_B6	IoX_B6
IoX_B7	IoX_B7
IoX_B8	IoX_B8
IoX_B9	IoX_B9
IoX_B10	IoX_B10
IoX_C1	N/A

Table 353: Interface (IF) mapping between system models ZBC2 and ZB2

ZBC2	ZB2
IF-B1	IF-B1
IF-B2	IF-B2
IF-B3	IF-B3
IF-C1	N/A

Table 354: IoX-IF pair mapping between system models ZBC2 and ZB2

ZBC2	ZB2
(IoX_B1, IF-Bl)	(IoX_B1, IF-Bl)
(IoX_B2, IF-B1)	(IoX_B2, IF-B1)
(IoX_B3, IF-B1)	(IoX_B3, IF-B1)
(IoX_B4, IF-B1)	(IoX_B4, IF-B1)
(IoX_B5, IF-B2)	(IoX_B5, IF-B2)
(IoX_B6, IF-B2)	(IoX_B6, IF-B2)
(IoX_B7, IF-B2)	(IoX_B7, IF-B2)
(IoX_B8, IF-B3)	(IoX_B8, IF-B3)
(IoX_B9, IF-B3)	(IoX_B9, IF-B3)
(IoX_B10, IF-B3)	(IoX_B10, IF-B3)
(IoX_C1, IF-C1)	N/A

Table 355: State mapping between system models ZBC2 and ZB2

ZBC2	ZB2
S_B@1	S_B@1
S_B@2	S_B@2

S_B@3	S_B@3

Table 356: Next state (N) and readout (R) functions mapping between system models ZBC2 and ZB2

XY Reference	ZBC2		ZB2	
	N trajectory	Final R	N trajectory	Final R
XY-S1	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))	((S_B@2, IoX_B1), S_B@1)	(S_B@1, IoX_B5)
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))	((S_B@3, IoX_B4), S_B@2), ((S_B@2, IoX_B1), S_B@1)	(S_B@1, IoX_B5)
XY-S2	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))	((S_B@1, IoX_B2), S_B@2)	(S_B@2, IoX_B6)
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))	((S_B@1, IoX_B2), S_B@2), ((S_B@2, IoX_B3), S_B@3),	(S_B@3, IoX_B7)
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))	((S_B@1, IoX_B2), S_B@2), ((S_B@2, IoX_B3), S_B3), ((S_B@3, IoX_B4), S_B@2)	(S_B@2, IoX_B6)
	((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))	((S_B@2, IoX_B3), S_B@3),	(S_B@3, IoX_B7)

	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))	((S_B@3, IoX_B4), S_B@2)	(S_B@2, IoX_B6)
XY-S3	((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))	N/A	N/A
	((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B1, IoX_C1)), S_BC@1)	(S_BC@1, (IoX_B5, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@1, (IoX_B2, IoX_C1)), S_BC@2), ((S_BC@2, (IoX_B3, IoX_C1)), S_BC@3), ((S_BC@3, (IoX_B4, IoX_C1)), S_BC@2)	(S_BC@2, (IoX_B6, IoX_C1))		
	((S_BC@2, IoX_B3), S_BC@3),	(S_BC@3, (IoX_B7, IoX_C1))		
	((S_BC@3, (IoX_B4,	(S_BC@2, (IoX_B6, IoX_C1))		

	IoX_C1)), S_BC@2)			

Table 357: Component mapping between system models ZBC2 and ZB2

ZBC2	ZB2
Components	Components
ZBD	ZBD
ZBE	ZBE
ZC	N/A

Table 358: System coupling recipe (SCR) mapping between system models ZBC2 and ZB2

ZBC2	ZB2
SCR	SCR
((Z_BD, Z_BE), (IoX_B8, IF-B3))	((Z_BD, Z_BE), (IoX_B8, IF-B3))
((Z_BD, Z_BE), (IoX_B9, IF-B3))	((Z_BD, Z_BE), (IoX_B9, IF-B3))
((Z_BD, Z_BE), (IoX_B10, IF-B3))	((Z_BD, Z_BE), (IoX_B10, IF-B3))
((Z_BD, Z_C), Ø)	((Z_BD, Z_C), Ø)
((Z_BE, Z_C), Ø)	((Z_BE, Z_C), Ø)

A.8 Supporting results of VRPS defined from SR

A.8.1 Proof of morphism between VRPS1 and SR

Table 359 provides the mapping between IoX with parameterization where applicable and Table 360 provides the mapping between IF with parameterization where applicable. The VRPS does not have a parameter morphism because there are no parameters defined for the VRPS. However, the VRPS is isomorphic to the combined SR subset of SR1, SR2, SR3, and SR4 due to the equality of the underlying mathematical structure defined as PSF_S2.

Table 359: Proof of morphic equivalence between IoX of the SR and VRPS1

SR		VRPS1	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Cold
On-command	• N/A	• N/A	Heat
No-light	• Lumen: <0.5 lm	• N/A	No delicious smell
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	Delicious smell
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 360: Proof of morphic equivalence between IF of the SR and VRPS1

SR		VRPS1	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Temperature IF
Light IF	• N/A	• N/A	Smell IF
Water IF	• N/A	• N/A	N/A

A.8.2 Proof of morphism between VRPS2 and SR

Table 361 provides the mapping between IoX with parameterization where applicable and Table 362 provides the mapping between IF with parameterization where applicable. As the results show, the VRPS has an identity isomorphism to the combined SR subset SR1, SR2, SR3, and SR4 due to the equality of the underlying mathematical structure defined as PSF_S2 and identity parameter morphism.

Table 361: Proof of morphic equivalence between IoX of the SR and VRPS2

SR		VRPS2	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-command
On-command	• N/A	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 362: Proof of morphic equivalence between IF of the SR and VRPS2

SR		VRPS2	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	On/off IF
Light IF	• N/A	• N/A	Light IF
Water IF	• N/A	• N/A	N/A

A.8.3 Proof of morphism between VRPS3 and SR

Table 363 provides the mapping between IoX with parameterization where applicable and Table 364 provides the mapping between IF with parameterization where applicable. As the results show, the VRPS has an identity isomorphism to the SR subset SR5 due to the equality of the underlying mathematical structure defined as PSF_S7 and identity parameter morphism.

Table 363: Proof of morphic equivalence between IoX of the SR and VRPS3

SR		VRPS3	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	N/A
On-command	• N/A	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 364: Proof of morphic equivalence between IF of the SR and VRPS3

SR		VRPS3	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	N/A
Light IF	• N/A	• N/A	N/A
Water IF	• N/A	• N/A	Water IF

A.8.4 Proof of morphism between VRPS4 and SR

Table 365 provides the mapping between IoX with parameterization where applicable and Table 366 provides the mapping between IF with parameterization where applicable. As the results show, the VRPS has a parameter isomorphism to the combined SR subset SR1, SR2, SR3, and SR4 due to the equality of the underlying mathematical structure defined as PSF_S2 and parameter morphism.

Table 365: Proof of morphic equivalence between IoX of the SR and VRPS4

SR		VRPS4	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-command
On-command	• N/A	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 450-495 nm [yellow] • Lumen: 200-1,000 lm	Blue-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 366: Proof of morphic equivalence between IF of the SR and VRPS4

SR		VRPS4	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	On/off IF
Light IF	• N/A	• N/A	Light IF
Water IF	• N/A	• N/A	N/A

A.8.5 Proof of morphism between VRPS5 and SR

Table 367 provides the mapping between IoX with parameterization where applicable and Table 368 provides the mapping between IF with parameterization where applicable. The VRPS does not have a parameter morphism because there are no parameters defined for the VRPS. However, the VRPS is isomorphic to the combined SR subset of SR1, SR2, SR3, and SR4 due to the equality of the underlying mathematical structure defined as PSF_S2.

Table 367: Proof of morphic equivalence between IoX of the SR and VRPS5

SR		VRPS5	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	0
On-command	• N/A	• N/A	1
No-light	• Lumen: <0.5 lm	• N/A	0
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	1
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 368: Proof of morphic equivalence between IF of the SR and VRPS5

SR		VRPS5	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Input IF
Light IF	• N/A	• N/A	Output IF
Water IF	• N/A	• N/A	N/A

A.9 Supporting results of SD adherence to SR

A.9.1 Proof of SD1 adherence to SR

Table 369 provides the mapping between IoX with parameterization where applicable and Table 370 provides the mapping between IF with parameterization where applicable. Because the SM to which the SD is a parameterization of has been proven to adhere to

PSF_S1 and the parameterization below adheres to the SR superset; the SD can be said to adhere to the SR.

Table 369: Proof of IoX adherence to SR for SD1

SR		SD1	
IoX	Parameterization		IoX
Off-command	• N/A	• Force: 0.5 N	Off-command
On-command	• N/A	• Force: 0.5 N	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 370: Proof of IF adherence to SR for SD1

SR		SD1	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.9.2 Proof of SD2 adherence to SR

Table 371 provides the mapping between IoX with parameterization where applicable and Table 372 provides the mapping between IF with parameterization where applicable. Because the SM to which the SD is a parameterization of has been proven to adhere to PSF_S1 and the parameterization below adheres to the SR superset; the SD can be said to adhere to the SR.

Table 371: Proof of IoX adherence to SR for SD2

SR	SD2

IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 372: Proof of IF adherence to SR for SD2

SR		SD2	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• N/A	• Diameter: 45 mm	Light IF

		• Material: clear plastic	
Water IF	• N/A	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

A.9.3 Proof of SD3 adherence to SR

Table 373 provides the mapping between IoX with parameterization where applicable and Table 374 provides the mapping between IF with parameterization where applicable. Because the SM to which the SD is a parameterization of has been proven to adhere to PSF_S1 and the parameterization below adheres to the SR superset; the SD can be said to adhere to the SR.

Table 373: Proof of IoX adherence to SR for SD3

SR		SD3	
IoX	Parameterization		IoX
Off-command	• N/A	• Force: 0.5 N	Off-command
On-command	• N/A	• Force: 0.5 N	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 374: Proof of IF adherence to SR for SD3

SR		SD3	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm	Water IF

		• Length: 254 mm • Material: black plastic	

A.9.4 Proof of SD4 adherence to SR problem space of functions

Table 375 provides the mapping between IoX with parameterization where applicable and Table 376 provides the mapping between IF with parameterization where applicable. Because the SM to which the SD is a parameterization of has been proven to adhere to PSF_S1 and the parameterization below adheres to the SR superset; the SD can be said to adhere to the SR.

Table 375: Proof of IoX adherence to SR for SD4

SR		SD4	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow]	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1

	• Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 376: Proof of IF adherence to SR for SD4

SR		SD4	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• N/A	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

A.10 Supporting results of VM defined from SR subsets

A.10.1 VM1 defined from SR

Because VM1 is SD1, this exercise was completed as part of the previous section. The results prove that VM1 is defined from the SR superset.

A.10.2 VM2 defined from SR

Because VM2 is SD2, this exercise was completed as part of the previous section. The results prove that VM2 is defined from the SR superset.

A.10.3 VM3 defined from SR

Because VM3 is SD3, this exercise was completed as part of the previous section. The results prove that VM3 is defined from the SR superset.

A.10.4 VM4 defined from SR

Because VM4 is SD4, this exercise was completed as part of the previous section. The results prove that VM4 is defined from the SR superset.

A.10.5 VM5 defined from SR

Table 377 provides the mapping between IoX with parameterization where applicable and Table 378 provides the mapping between IF with parameterization where applicable. Because the SM to which the VM is an instantiation of has been proven to adhere to PSF_S7 and the instantiation below adheres to the SR subset SR5 and the function based on XY-S3; the VM can be said to adhere to the SR5 alone. The VM does not adhere to SR1, SR2, SR3, and SR4, which are functions based on XY-S1 and XY-S2; and, therefore, does not adhere to the SR superset.

Table 377: Proof of IoX adherence to SR for VM5

SR		VM5	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	N/A
On-command	• N/A	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 378: Proof of IF adherence to SR for VM5

SR		VM5	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	N/A
Light IF	• N/A	• N/A	N/A
Water IF	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.10.6 VM6 defined from SR

Table 379 provides the mapping between IoX with parameterization where applicable and Table 380 provides the mapping between IF with parameterization where applicable. The SM to which the VM is an instantiation of has been proven to adhere to PSF_S2, PSF_S3, and PSF_S4 and the parameterization below adheres to the SR subset SR1, SR2, SR3, and SR4 and the functions based on XY-S1 and XY-S2. The VM does not adhere to SR5, which are functions based on XY-S3; and, therefore, does not adhere to the SR superset.

Table 379: Proof of IoX adherence to SR for VM6

SR		VM6	
IoX	Parameterization		IoX
Off-command	• N/A	• Force: 0.5 N	Off-command
On-command	• N/A	• Force: 0.5 N	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 380: Proof of IF adherence to SR for VM6

SR		VM6	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• N/A	• N/A	N/A

A.10.7 VM7 defined from SR

Table 381 provides the mapping between IoX with parameterization where applicable and Table 382 provides the mapping between IF with parameterization where applicable. The VM is a symbolic change with no parameterization of to the SM that has been proven to adhere to PSF_S2, PSF_S3, and PSF_S4 and; and, therefore, the VM does not does not adhere to any of the SR.

Table 381: Proof of IoX adherence to SR for VM7

SR		VM7	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	0
On-command	• N/A	• N/A	1
No-light	• Lumen: <0.5 lm	• N/A	0
Yellow-light	• Wavelength: 570-590 nm [yellow]	• N/A	1

	• Lumen: 200-1,000 lm		
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 382: Proof of IF adherence to SR for VM7

SR		VM7	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Input IF
Light IF	• N/A	• N/A	Output IF
Water IF	• N/A	• N/A	N/A

A.10.8 VM8 defined from SR

Table 383 provides the mapping between IoX with parameterization where applicable and Table 384 provides the mapping between IF with parameterization where applicable. The SM to which the VM is a parameterization of has been proven to adhere to PSF_S2, PSF_S3, and PSF_S4 and the parameterization below does not adhere to the SR subset SR1, SR2, SR3, and SR4 and the functions based on XY-S1 and XY-S2. Furthermore, the VM does not adhere to SR5, which are functions based on XY-S3; and, therefore, does not adhere to the SR superset.

Table 383: Proof of IoX adherence to SR for VM8

SR		VM8	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light

Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 384: Proof of IF adherence to SR for VM8

SR		VM8	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• N/A	• N/A	N/A

A.10.9 VM9 defined from SR

Table 385 provides the mapping between IoX with parameterization where applicable and Table 386 provides the mapping between IF with parameterization where applicable. The SM to which the VM is a parameterization of has been proven to adhere to PSF_S2, PSF_S3, and PSF_S4 and the parameterization below does not adhere to the SR subset SR1, SR2, SR3, and SR4 and the functions based on XY-S1 and XY-S2. Furthermore, the VM does not adhere to SR5, which are functions based on XY-S3; and, therefore, does not adhere to the SR superset.

Table 385: Proof of IoX adherence to SR for VM9

SR		VM9	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll	On-command 2

		• Position(s): 240 degrees • Direction: counter-clockwise	
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [blue] • Lumen: 250 lm	Blue-light 1
		• Wavelength: 590 nm [blue] • Lumen: 750 lm	Blue-light 2
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 386: Proof of IF adherence to SR for VM9

SR		VM9	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• N/A	• N/A	N/A

A.10.10 VM10 defined from SR

Table 387 provides the mapping between IoX with parameterization where applicable and Table 388 provides the mapping between IF with parameterization where applicable. The SM to which the VM is a parameterization of has been proven to adhere to PSF_S2, PSF_S3, and PSF_S4 and the parameterization below does not adhere to the SR subset SR1, SR2, SR3, and SR4 and the functions based on XY-S1 and XY-S2. Furthermore, the VM does not adhere to SR5, which are functions based on XY-S3; and, therefore, does not adhere to the SR superset.

Table 387: Proof of IoX adherence to SR for VM10

SR		VM10	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Green to Red
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	Red to Green
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	Green to Blue
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	Blue to Green
No-light	• Lumen: <0.5 lm	• Wavelength: 650 nm [red]	Red Ink
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 510 nm [green]	Green Ink
		• Wavelength: 475 nm [blue]	Blue Ink
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 388: Proof of IF adherence to SR for VM10

SR		VM10	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 5 mm • Material: black plastic	Color Change IF

Light IF	• N/A	• Diameter: 2 mm • Material: brass	Ink IF
Water IF	• N/A	• N/A	N/A

A.10.11 VM11 defined from SR

Table 389 provides the mapping between IoX with parameterization where applicable and Table 390 provides the mapping between IF with parameterization where applicable. The VM is a symbolic change with no parameterization of to the SM that has been proven to adhere to PSF_S2, PSF_S3, and PSF_S4 and; and, therefore, the VM does not does not adhere to any of the SR.

Table 389: Proof of IoX adherence to SR for VM11

SR			VM11
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Cold
On-command	• N/A	• N/A	Hot
No-light	• Lumen: <0.5 lm	• N/A	No delicious smell
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	Delicious
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 390: Proof of IF adherence to SR for VM11

SR			VM11
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Oven IF
Light IF	• N/A	• N/A	Kitchen Air IF
Water IF	• N/A	• N/A	N/A

A.10.12 VM12 defined from SR

Table 391 provides the mapping between IoX with parameterization where applicable and Table 392 provides the mapping between IF with parameterization where applicable. The SM to which the VM is a parameterization of has been proven to adhere to PSF_S2, PSF_S3, and PSF_S4 and the parameterization below adheres to the SR subset SR1, SR2, SR3, and SR4 and the functions based on XY-S1 and XY-S2. However, the VM does not adhere to the symbolism or to SR5, which are functions based on XY-S3; and, therefore, does not adhere to the SR superset.

Table 391: Proof of IoX adherence to SR for VM12

SR			VM12

IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-trigger
On-command	• N/A	• N/A	On-trigger
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 392: Proof of IF adherence to SR for VM12

SR		VM12	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Trigger IF
Light IF	• N/A	• N/A	Light IF
Water IF	• N/A	• N/A	N/A

A.10.13 VM13 defined from SR

Table 393 provides the mapping between IoX with parameterization where applicable and Table 394 provides the mapping between IF with parameterization where applicable. The SM to which the VM is a parameterization of has been proven to adhere to PSF_S2, PSF_S3, and PSF_S4 and the parameterization below adheres to the SR subset SR3 and SR4 and the functions based on XY-2. However, the VM does not adhere to the symbolism or to SR1, SR2, and SR5, which are functions based on XY-S1 and XY-S3; and, therefore, does not adhere to the SR superset.

Table 393: Proof of IoX adherence to SR for VM13

SR		VM13	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-command
On-command	• N/A	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-off
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	Radio-on
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 394: Proof of IF adherence to SR for VM13

SR		VM13	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Off IF
Light IF	• N/A	• N/A	Radio Display IF
Water IF	• N/A	• N/A	N/A

A.10.14 VM14 defined from SR

Table 395 provides the mapping between IoX with parameterization where applicable and Table 396 provides the mapping between IF with parameterization where applicable. Because the SM to which the VM is a parameterization of has been proven to adhere to PSF_S7 and the parameterization below adheres to the SR subset SR5 and the function based on XY-S3; the VM can be said to adhere to the SR5 alone. The VM does not adhere to SR1, SR2, SR3, and SR4, which are functions based on XY-S1 and XY-S2; and, therefore, does not adhere to the SR superset.

Table 395: Proof of IoX adherence to SR for VM14

SR		VM14	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	N/A
On-command	• N/A	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: -5-1000 atm • Humidity: 0-100%	Water

Table 396: Proof of IF adherence to SR for VM14

SR		VM14	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	N/A
Light IF	• N/A	• N/A	N/A
Water IF	• N/A	• N/A	Water IF

A.10.15 VM15 defined from SR

Table 397 provides the mapping between IoX with parameterization where applicable and Table 398 provides the mapping between IF with parameterization where applicable.

Because the SM to which the VM is a parameterization of has been proven to adhere to PSF_S7 and the parameterization below adheres to the SR subset SR5 and the function based on XY-S3; the VM can be said to adhere to the SR5 alone. The VM does not adhere to SR1, SR2, SR3, and SR4, which are functions based on XY-S1 and XY-S2; and, therefore, does not adhere to the SR superset.

Table 397: Proof of IoX adherence to SR for VM15

SR		VM15	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	N/A
On-command	• N/A	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 398: Proof of IF adherence to SR for VM15

SR		VM15	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	N/A
Light IF	• N/A	• N/A	N/A
Water IF	• N/A	• N/A	Water IF

A.10.16 VM16 defined from SR

Table 399 provides the mapping between IoX with parameterization where applicable and Table 400 provides the mapping between IF with parameterization where applicable. The SM to which the VM is a parameterization of has been proven to adhere to PSF_S1 and the parameterization below adheres to the SR subset SR1, SR2, SR3, SR4, and SR5 and the functions based on XY-S1, XY-S2, and XY-S2. However, the VM does not adhere to the symbolism; and, therefore, does not adhere to the SR superset.

Table 399: Proof of IoX adherence to SR for VM16

SR		VM16	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-trigger
On-command	• N/A	• N/A	On-trigger
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light

Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 400: Proof of IF adherence to SR for VM16

SR		VM16	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Trigger IF
Light IF	• N/A	• N/A	Light IF
Water IF	• N/A	• N/A	N/A

A.10.17 VM17 defined from SR

Table 401 provides the mapping between IoX with parameterization where applicable and Table 402 provides the mapping between IF with parameterization where applicable. The SM to which the VM is a parameterization of has been proven to adhere to PSF_S2, PSF_S3, and PSF_S4 and the parameterization below adheres to the SR subset SR3, SR4, and SR5 and the functions based on XY-2 and XY-S3. However, the VM does not adhere to the symbolism or to parameters of SR1 and SR2, which are functions based on XY-S1; and, therefore, does not adhere to the SR superset.

Table 401: Proof of IoX adherence to SR for VM17

SR		VM17	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-command
On-command	• N/A	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-off
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	Radio-on
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 402: Proof of IF adherence to SR for VM17

SR		VM17	
IF	Parameterization		IF

On/off IF	• N/A	• N/A	Trigger IF
Light IF	• N/A	• N/A	Light IF
Water IF	• N/A	• N/A	Water IF

A.10.18 VM18 defined from SR

Table 403 provides the mapping between IoX with parameterization where applicable and Table 404 provides the mapping between IF with parameterization where applicable. The SM to which the VM is a parameterization of has been proven to adhere to PSF_S1 and the parameterization below adheres to the SR subset SR1, SR2, SR3, SR4, and SR5 and the functions based on XY-S1, XY-S2, and XY-S2; and, therefore, adhere to the SR superset.

Table 403: Proof of IoX adherence to SR for VM18

SR		VM18	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-command
On-command	• N/A	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: -5-1,000 atm • Humidity: 0-100%	Water

Table 404: Proof of IF adherence to SR for VM18

SR		VM18	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	On/off IF
Light IF	• N/A	• N/A	Light IF
Water IF	• N/A	• N/A	Water IF

A.11 Support results from VM defined from VRPS

A.11.1 VM defined from VRPS1

A.11.1.1 VM1 defined from VRPS1

Table 405 provides the mapping between IoX with parameterization where applicable and Table 406 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 405: Proof of IoX adherence to VRPS1 for VM1

VRPS1		VM1	
IoX	Parameterization		IoX
Cold	• N/A	• Force: 0.5 N	Off-command
Heat	• N/A	• Force: 0.5 N	On-command
No-delicious smell	• N/A	• Lumen: <0.5 lm	No-light
Delicious smell	• N/A	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 406: Proof of IF adherence to VRPS1 for VM1

VRPS1		VM1	
IF	Parameterization		IF
Temperature IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Smell IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.1.2 VM2 defined from VRPS1

Table 407 provides the mapping between IoX with parameterization where applicable and Table 408 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 407: Proof of IoX adherence to VRPS1 for VM2

VRPS1		VM2	
IoX	Parameterization		IoX
Cold	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
Heat	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-delicious smell	• N/A	• Lumen: <0.5 lm	No-light
Delicious smell	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
N/A	• N/A	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 408: Proof of IF adherence to VRPS1 for VM1

VRPS1		VM2	
IF	Parameterization		IF
Temperature IF	• N/A	• Diameter: 50 mm	On/off IF

		• Material: black plastic	
Smell IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

A.11.1.3 VM3 defined from VRPS1

Table 409 provides the mapping between IoX with parameterization where applicable and Table 410 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 409: Proof of IoX adherence to VRPS1 for VM3

VRPS1		VM3	
IoX	Parameterization		IoX
Cold	• N/A	• Force: 0.5 N	Off-command
Heat	• N/A	• Force: 0.5 N	On-command
No-delicious smell	• N/A	• Lumen: <0.5 lm	No-light
Delicious smell	• N/A	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 410: Proof of IF adherence to VRPS1 for VM3

VRPS1		VM3	
IF	Parameterization		IF
Temperature IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Smell IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF

N/A	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.1.4 VM4 defined from VRPS1

Table 411 provides the mapping between IoX with parameterization where applicable and Table 412 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 411: Proof of IoX adherence to VRPS1 for VM4

VRPS1		VM4	
IoX	Parameterization		IoX
Cold	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
Heat	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-delicious smell	• N/A	• Lumen: <0.5 lm	No-light

Delicious smell	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
N/A	• N/A	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 412: Proof of IF adherence to VRPS1 for VM4

VRPS1		VM4	
IF	Parameterization		IF
Temperature IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Smell IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

A.11.1.5 VM5 defined from VRPS1

Table 413 provides the mapping between IoX with parameterization where applicable and Table 414 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 413: Proof of IoX adherence to VRPS1 for VM5

VRPS1		VM5	
IoX	Parameterization		IoX
Cold	• N/A	• N/A	N/A
Heat	• N/A	• N/A	N/A
No-delicious smell	• N/A	• N/A	N/A
Delicious smell	• N/A	• N/A	N/A
N/A	• N/A	• Pressure: 1-5 atm	Water

		• Humidity: 0-100%	

Table 414: Proof of IF adherence to VRPS1 for VM5

VRPS1		VM5	
IF	Parameterization		IF
Temperature IF	• N/A	• N/A	N/A
Smell IF	• N/A	• N/A	N/A
N/A	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.1.6 VM6 defined from VRPS1

Table 415 provides the mapping between IoX with parameterization where applicable and Table 416 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 415: Proof of IoX adherence to VRPS1 for VM6

VRPS1		VM6	
IoX	Parameterization		IoX
Cold	• N/A	• Force: 0.5 N	Off-command
Heat	• N/A	• Force: 0.5 N	On-command
No-delicious smell	• N/A	• Lumen: <0.5 lm	No-light
Delicious smell	• N/A	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• N/A	N/A

Table 416: Proof of IF adherence to VRPS1 for VM6

VRPS1		VM6	
IF	Parameterization		IF
Temperature IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Smell IF	• N/A	• Diameter: 57 mm	Light IF

		• Material: clear plastic	
N/A	• N/A	• N/A	N/A

A.11.1.7 VM7 defined from VRPS1

Table 417 provides the mapping between IoX with parameterization where applicable and Table 418 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is symbolically changed to form the VM has been proven to adhere to. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 417: Proof of IoX adherence to VRPS1 for VM7

VRPS1		VM7	
IoX	Parameterization		IoX
Cold	• N/A	• N/A	0
Heat	• N/A	• N/A	1
No-delicious smell	• N/A	• N/A	0
Delicious smell	• N/A	• N/A	1
N/A	• N/A	• N/A	N/A

Table 418: Proof of IF adherence to VRPS1 for VM7

VRPS1		VM7	
IF	Parameterization		IF
Temperature IF	• N/A	• N/A	Input IF
Smell IF	• N/A	• N/A	Output IF
N/A	• N/A	• N/A	N/A

A.11.1.8 VM8 defined from VRPS1

Table 419 provides the mapping between IoX with parameterization where applicable and Table 420 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 419: Proof of IoX adherence to VRPS1 for VM8

VRPS1		VM8	
IoX	Parameterization		IoX
Cold	• N/A	• Torque: 0.5 Nm • Rotation: roll	Off-command

		• Position: 0 degrees • Direction: clockwise	
Heat	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command
No-delicious smell	• N/A	• Lumen: <0.5 lm	No-light
Delicious smell	• N/A	• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light
N/A	• N/A	• N/A	N/A

Table 420: Proof of IF adherence to VRPS1 for VM8

VRPS1		VM8	
IF	Parameterization		IF
Temperature IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Smell IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• N/A	N/A

A.11.1.9 VM9 defined from VRPS1

Table 421 provides the mapping between IoX with parameterization where applicable and Table 422 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 421: Proof of IoX adherence to VRPS1 for VM9

VRPS1		VM9	
IoX	Parameterization		IoX
Cold	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees	Off-command

		• Direction: clockwise	
Heat	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-delicious smell	• N/A	• Lumen: <0.5 lm	No-light
Delicious smell	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Blue-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Blue-light 2
	•	• N/A	N/A

Table 422: Proof of IF adherence to VRPS1 for VM9

VRPS1		VM9	
IF	Parameterization		IF
Temperature IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Smell IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
N/A	• N/A	• N/A	N/A

A.11.1.10 VM10 defined from VRPS1

Table 423 provides the mapping between IoX with parameterization where applicable and Table 424 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 423: Proof of IoX adherence to VRPS1 for VM10

VRPS1		VM10	
IoX	Parameterization		IoX
Cold	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Green to Red
Heat	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	Red to Green
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	Green to Blue
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	Blue to Green
No-delicious smell	• N/A	• Wavelength: 650 nm [red]	Red Ink
Delicious smell	• N/A	• Wavelength: 510 nm [green]	Green Ink
		• Wavelength: 475 nm [blue]	Blue Ink
	•	• N/A	N/A

Table 424: Proof of IF adherence to VRPS1 for VM10

VRPS1		VM10	
IF	Parameterization		IF
Temperature IF	• N/A	• Diameter: 5 mm • Material: black plastic	Color Change IF
Smell IF	• N/A	• Diameter: 2 mm • Material: brass	Ink IF
N/A	• N/A	• N/A	N/A

A.11.1.11 VM11 defined from VRPS1

Table 425 provides the mapping between IoX with parameterization where applicable and Table 426 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is symbolically changed to form the VM has been proven to not adhere to. Therefore, the VM can be defined on the basis of this VRPS.

Table 425: Proof of IoX adherence to VRPS1 for VM11

VRPS1		VM11	
IoX	Parameterization		IoX
Cold	• N/A	• N/A	Cold
Heat	• N/A	• N/A	Hot
No-delicious smell	• N/A	• N/A	No delicious smell
Delicious smell	• N/A	• N/A	Delicious
N/A	• N/A	• N/A	N/A

Table 426: Proof of IF adherence to VRPS1 for VM11

VRPS1		VM11	
IF	Parameterization		IF
Temperature IF	• N/A	• N/A	Oven IF
Smell IF	• N/A	• N/A	Kitchen Air IF
N/A	• N/A	• N/A	N/A

A.11.1.12 VM12 defined from VRPS1

Table 427 provides the mapping between IoX with parameterization where applicable and Table 428 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 427: Proof of IoX adherence to VRPS1 for VM12

VRPS1		VM12	
IoX	Parameterization		IoX
Cold	• N/A	• N/A	Off-trigger
Heat	• N/A	• N/A	On-trigger
No-delicious smell	• N/A	• Lumen: <0.5 lm	No-light
Delicious smell	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
N/A	• N/A	• N/A	N/A

Table 428: Proof of IF adherence to VRPS1 for VM12

VRPS1		VM12	
IF	Parameterization		IF
Temperature IF	• N/A	• N/A	Trigger IF
Smell IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	N/A

A.11.1.13 VM13 defined from VRPS1

Table 429 provides the mapping between IoX with parameterization where applicable and Table 430 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 429: Proof of IoX adherence to VRPS1 for VM13

VRPS1		VM13	
IoX	Parameterization		IoX
Cold	• N/A	• N/A	Off-command
Heat	• N/A	• N/A	On-command
No-delicious smell	• N/A	• Lumen: <0.5	Radio-off
Delicious smell	• N/A	• N/A	Radio-on
N/A	• N/A	• N/A	N/A

Table 430: Proof of IF adherence to VRPS1 for VM13

VRPS1		VM13	
IF	Parameterization		IF
Temperature IF	• N/A	• N/A	Off IF
Smell IF	• N/A	• N/A	Radio Display IF

N/A	• N/A	• N/A	N/A

A.11.1.14 VM14 defined from VRPS1

Table 431 provides the mapping between IoX with parameterization where applicable and Table 432 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 431: Proof of IoX adherence to VRPS1 for VM14

VRPS1		VM14	
IoX	Parameterization		IoX
Cold	• N/A	• N/A	N/A
Heat	• N/A	• N/A	N/A
No-delicious smell	• N/A	• N/A	N/A
Delicious smell	• N/A	• N/A	N/A
N/A	• N/A	• Pressure: -5-1000 atm • Humidity: 0-100%	Water

Table 432: Proof of IF adherence to VRPS1 for VM14

VRPS1		VM14	
IF	Parameterization		IF
Temperature IF	• N/A	• N/A	N/A
Smell IF	• N/A	• N/A	N/A
N/A	• N/A	• N/A	Water IF

A.11.1.15 VM15 defined from VRPS1

Table 433 provides the mapping between IoX with parameterization where applicable and Table 434 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 433: Proof of IoX adherence to VRPS1 for VM15

VRPS1		VM15	
IoX	Parameterization		IoX
Cold	• N/A	• N/A	N/A
Heat	• N/A	• N/A	N/A
No-delicious smell	• N/A	• N/A	N/A

Delicious smell	• N/A	• N/A	N/A
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 434: Proof of IF adherence to VRPS1 for VM15

VRPS1		VM15	
IF	Parameterization		IF
Temperature IF	• N/A	• N/A	N/A
Smell IF	• N/A	• N/A	N/A
N/A	• N/A	• N/A	Water IF

A.11.1.16 VM16 defined from VRPS1

Table 435 provides the mapping between IoX with parameterization where applicable and Table 436 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 435: Proof of IoX adherence to VRPS1 for VM16

VRPS1		VM16	
IoX	Parameterization		IoX
Cold	• N/A	• N/A	Off-trigger
Heat	• N/A	• N/A	On-trigger
No-delicious smell	• N/A	• Lumen: <0.5 lm	No-light
Delicious smell	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 436: Proof of IF adherence to VRPS1 for VM16

VRPS1		VM16	
IF	Parameterization		IF
Temperature IF	• N/A	• N/A	Trigger IF
Smell IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	N/A

A.11.1.17 VM17 defined from VRPS1

Table 437 provides the mapping between IoX with parameterization where applicable and Table 438 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 437: Proof of IoX adherence to VRPS1 for VM17

VRPS1		VM17	
IoX	Parameterization		IoX
Cold	• N/A	• N/A	Off-command
Heat	• N/A	• N/A	On-command
No-delicious smell	• N/A	• Lumen: <0.5	Radio-off
Delicious smell	• N/A	• N/A	Radio-on
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 438: Proof of IF adherence to VRPS1 for VM17

VRPS1		VM17	
IF	Parameterization		IF
Temperature IF	• N/A	• N/A	Trigger IF
Smell IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	Water IF

A.11.1.18 VM18 defined from VRPS1

Table 439 provides the mapping between IoX with parameterization where applicable and Table 440 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Furthermore, had the VRPS been parameterized, this result would be further validated. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 439: Proof of IoX adherence to VRPS1 for VM18

VRPS1		VM18	
IoX	Parameterization		IoX
Cold	• N/A	• N/A	Off-command
Heat	• N/A	• N/A	On-command
No-delicious smell	• N/A	• Lumen: <0.5 lm	No-light
Delicious smell	• N/A	• Wavelength: 580 nm [yellow]	Yellow-light

		• Lumen: 500 lm	
N/A	• N/A	• Pressure: -5-1,000 atm • Humidity: 0-100%	Water

Table 440: Proof of IF adherence to VRPS1 for VM18

VRPS1		VM18	
IF	Parameterization		IF
Temperature IF	• N/A	• N/A	On/off IF
Smell IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	Water IF

A.11.2 VM defined from VRPS2

A.11.2.1 VM1 defined from VRPS2

Table 441 provides the mapping between IoX with parameterization where applicable and Table 442 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 441: Proof of IoX adherence to VRPS2 for VM1

VRPS2		VM1	
IoX	Parameterization		IoX
Off-command	• N/A	• Force: 0.5 N	Off-command
On-command	• N/A	• Force: 0.5 N	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 442: Proof of IF adherence to VRPS2 for VM1

VRPS2		VM1	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF

Light IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.2.2 VM2 defined from VRPS2

Table 443 provides the mapping between IoX with parameterization where applicable and Table 444 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 443: Proof of IoX adherence to VRPS2 for VM2

VRPS2		VM2	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3

No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
N/A	• N/A	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 444: Proof of IF adherence to VRPS2 for VM2

VRPS2		VM2	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

A.11.2.3 VM3 defined from VRPS2

Table 445 provides the mapping between IoX with parameterization where applicable and Table 446 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 445: Proof of IoX adherence to VRPS2 for VM3

VRPS2		VM3	
IoX	Parameterization		IoX
Off-command	• N/A	• Force: 0.5 N	Off-command
On-command	• N/A	• Force: 0.5 N	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light

Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 446: Proof of IF adherence to VRPS2 for VM3

VRPS2		VM3	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 14,478 mm • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.2.4 VM4 defined from VRPS2

Table 447 provides the mapping between IoX with parameterization where applicable and Table 448 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 447: Proof of IoX adherence to VRPS2 for VM4

VRPS2		VM4	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll	On-command 1

		• Position(s): 120 degrees • Direction: counter-clockwise	
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
N/A	• N/A	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 448: Proof of IF adherence to VRPS2 for VM4

VRPS2		VM4	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

A.11.2.5 VM5 defined from VRPS2

Table 449 provides the mapping between IoX with parameterization where applicable and Table 450 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 449: Proof of IoX adherence to VRPS2 for VM5

VRPS2		VM5	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	N/A
On-command	• N/A	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	N/A
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 450: Proof of IF adherence to VRPS2 for VM5

VRPS2		VM5	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	N/A
Light IF	• N/A	• N/A	N/A
N/A	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.2.6 VM6 defined from VRPS2

Table 451 provides the mapping between IoX with parameterization where applicable and Table 452 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 451: Proof of IoX adherence to VRPS2 for VM6

VRPS2		VM6	
IoX	Parameterization		IoX
Off-command	• N/A	• Force: 0.5 N	Off-command
On-command	• N/A	• Force: 0.5 N	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• N/A	N/A

Table 452: Proof of IF adherence to VRPS2 for VM6

VRPS2		VM6	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• N/A	N/A

A.11.2.7 VM7 defined from VRPS2

Table 453 provides the mapping between IoX with parameterization where applicable and Table 454 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS parameterization. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 453: Proof of IoX adherence to VRPS2 for VM7

VRPS2		VM7	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	0
On-command	• N/A	• N/A	1
No-light	• Lumen: <0.5 lm	• N/A	0
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	1
N/A	• N/A	• N/A	N/A

Table 454: Proof of IF adherence to VRPS2 for VM7

VRPS2		VM7	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Input IF
Light IF	• N/A	• N/A	Output IF
N/A	• N/A	• N/A	N/A

A.11.2.8 VM8 defined from VRPS2

Table 455 provides the mapping between IoX with parameterization where applicable and Table 456 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS parameterization. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 455: Proof of IoX adherence to VRPS2 for VM8

VRPS2		VM8	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light
N/A	• N/A	• N/A	N/A

Table 456: Proof of IF adherence to VRPS2 for VM8

VRPS2		VM8	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF

Light IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• N/A	N/A

A.11.2.9 VM9 defined from VRPS2

Table 457 provides the mapping between IoX with parameterization where applicable and Table 458 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS parameterization. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 457: Proof of IoX adherence to VRPS2 for VM9

VRPS2		VM9	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow]	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Blue-light 1

	• Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Blue-light 2
N/A	• N/A	• N/A	N/A

Table 458: Proof of IF adherence to VRPS2 for VM9

VRPS2		VM9	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
N/A	• N/A	• N/A	N/A

A.11.2.10 VM10 defined from VRPS2

Table 459 provides the mapping between IoX with parameterization where applicable and Table 460 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS parameterization. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 459: Proof of IoX adherence to VRPS2 for VM10

VRPS2		VM10	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Green to Red
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	Red to Green
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees	Green to Blue

		• Direction: counter-clockwise	
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	Blue to Green
No-light	• Lumen: <0.5 lm	• Wavelength: 650 nm [red]	Red Ink
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 510 nm [green]	Green Ink
		• Wavelength: 475 nm [blue]	Blue Ink
N/A	• N/A	• N/A	N/A

Table 460: Proof of IF adherence to VRPS2 for VM10

VRPS2		VM10	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 5 mm • Material: black plastic	Color Change IF
Light IF	• N/A	• Diameter: 2 mm • Material: brass	Ink IF
N/A	• N/A	• N/A	N/A

A.11.2.11 VM11 defined from VRPS2

Table 461 provides the mapping between IoX with parameterization where applicable and Table 462 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS parameterization. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 461: Proof of IoX adherence to VRPS2 for VM11

VRPS2		VM11	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Cold
On-command	• N/A	• N/A	Hot
No-light	• Lumen: <0.5 lm	• N/A	No delicious smell
Yellow-light	• Wavelength: 570-590 nm [yellow]	• N/A	Delicious

	• Lumen: 200-1,000 lm		
N/A	• N/A	• N/A	N/A

Table 462: Proof of IF adherence to VRPS2 for VM11

VRPS2		VM11	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Oven IF
Light IF	• N/A	• N/A	Kitchen Air IF
N/A	• N/A	• N/A	N/A

A.11.2.12 VM12 defined from VRPS2

Table 463 provides the mapping between IoX with parameterization where applicable and Table 464 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. Although, the VM does adhere to the VRPS parameterization, the VM does not adhere to the symbolism of the VRPS. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 463: Proof of IoX adherence to VRPS2 for VM12

VRPS2		VM12	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-trigger
On-command	• N/A	• N/A	On-trigger
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
N/A	• N/A	• N/A	N/A

Table 464: Proof of IF adherence to VRPS2 for VM12

VRPS2		VM12	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Trigger IF
Light IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	N/A

A.11.2.13 VM13 defined from VRPS2

Table 465 provides the mapping between IoX with parameterization where applicable and Table 466 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS symbolism or the parameterization. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 465: Proof of IoX adherence to VRPS2 for VM13

VRPS2		VM13	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-command
On-command	• N/A	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-off
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	Radio-on
N/A	• N/A	• N/A	N/A

Table 466: Proof of IF adherence to VRPS2 for VM13

VRPS2		VM13	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Off IF
Light IF	• N/A	• N/A	Radio Display IF
N/A	• N/A	• N/A	N/A

A.11.2.14 VM14 defined from VRPS2

Table 467 provides the mapping between IoX with parameterization where applicable and Table 468 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 467: Proof of IoX adherence to VRPS2 for VM14

VRPS2		VM14	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	N/A
On-command	• N/A	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Yellow-light	• Wavelength: 570-590 nm [yellow]	• N/A	N/A

	• Lumen: 200-1,000 lm		
N/A	• N/A	• Pressure: -5-1000 atm • Humidity: 0-100%	Water

Table 468: Proof of IF adherence to VRPS2 for VM14

VRPS2		VM14	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	N/A
Light IF	• N/A	• N/A	N/A
N/A	• N/A	• N/A	Water IF

A.11.2.15 VM15 defined from VRPS2

Table 469 provides the mapping between IoX with parameterization where applicable and Table 470 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 469: Proof of IoX adherence to VRPS2 for VM15

VRPS2		VM15	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	N/A
On-command	• N/A	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	N/A
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 470: Proof of IF adherence to VRPS2 for VM15

VRPS2		VM15	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	N/A
Light IF	• N/A	• N/A	N/A
N/A	• N/A	• N/A	Water IF

A.11.2.16 VM16 defined from VRPS2

Table 471 provides the mapping between IoX with parameterization where applicable and Table 472 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. Although, the VM does adhere to the VRPS parameterization, the VM does not adhere to the symbolism of the VRPS. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 471: Proof of IoX adherence to VRPS2 for VM16

VRPS2		VM16	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-trigger
On-command	• N/A	• N/A	On-trigger
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 472: Proof of IF adherence to VRPS2 for VM16

VRPS2		VM16	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Trigger IF
Light IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	N/A

A.11.2.17 VM17 defined from VRPS2

Table 473 provides the mapping between IoX with parameterization where applicable and Table 474 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS parameterization. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 473: Proof of IoX adherence to VRPS2 for VM17

VRPS2		VM17	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-command

On-command	• N/A	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-off
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• N/A	Radio-on
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 474: Proof of IF adherence to VRPS2 for VM17

VRPS2		VM17	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Trigger IF
Light IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	Water IF

A.11.2.18 VM18 defined from VRPS2

Table 475 provides the mapping between IoX with parameterization where applicable and Table 476 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 475: Proof of IoX adherence to VRPS2 for VM18

VRPS2		VM18	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-command
On-command	• N/A	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• Pressure: -5-1,000 atm • Humidity: 0-100%	Water

Table 476: Proof of IF adherence to VRPS2 for VM18

VRPS2		VM18	

IF	Parameterization		IF
On/off IF	• N/A	• N/A	On/off IF
Light IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	Water IF

A.11.3 VM defined from VRPS3

A.11.3.1 VM1 defined from VRPS3

Table 477 provides the mapping between IoX with parameterization where applicable and Table 478 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 477: Proof of IoX adherence to VRPS3 for VM1

VRPS3		VM1	
IoX	Parameterization		IoX
N/A	• N/A	• Force: 0.5 N	Off-command
N/A	• N/A	• Force: 0.5 N	On-command
N/A	• N/A	• Lumen: <0.5 lm	No-light
N/A	• N/A	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 478: Proof of IF adherence to VRPS3 for VM1

VRPS3		VM1	
IF	Parameterization		IF
N/A	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
N/A	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

	• Material: black plastic		

A.11.3.2 VM2 defined from VRPS3

Table 479 provides the mapping between IoX with parameterization where applicable and Table 480 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 479: Proof of IoX adherence to VRPS3 for VM2

VRPS3		VM2	
IoX	Parameterization		IoX
N/A	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
N/A	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
N/A	• N/A	• Lumen: <0.5 lm	No-light
N/A	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow]	Yellow-light 2

		• Lumen: 750 lm	
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 480: Proof of IF adherence to VRPS3 for VM2

VRPS3		VM2	
IF	Parameterization		IF
N/A	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
N/A	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

A.11.3.3 VM3 defined from VRPS3

Table 481 provides the mapping between IoX with parameterization where applicable and Table 482 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 481: Proof of IoX adherence to VRPS3 for VM3

VRPS3		VM3	
IoX	Parameterization		IoX
N/A	• N/A	• Force: 0.5 N	Off-command
N/A	• N/A	• Force: 0.5 N	On-command
N/A	• N/A	• Lumen: <0.5 lm	No-light
N/A	• N/A	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 482: Proof of IF adherence to VRPS3 for VM3

VRPS3		VM3	
IF	Parameterization		IF
N/A	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
N/A	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.3.4 VM4 defined from VRPS3

Table 483 provides the mapping between IoX with parameterization where applicable and Table 484 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 483: Proof of IoX adherence to VRPS3 for VM4

VRPS3		VM4	
IoX	Parameterization		IoX
N/A	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
N/A	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll	On-command 2

		• Position(s): 240 degrees • Direction: counter-clockwise	
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
N/A	• N/A	• Lumen: <0.5 lm	No-light
N/A	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 484: Proof of IF adherence to VRPS3 for VM4

VRPS3		VM4	
IF	Parameterization		IF
N/A	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
N/A	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

A.11.3.5 VM5 defined from VRPS3

Table 485 provides the mapping between IoX with parameterization where applicable and Table 486 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has

been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 485: Proof of IoX adherence to VRPS3 for VM5

VRPS3		VM5	
IoX	Parameterization		IoX
N/A	• N/A	• N/A	N/A
N/A	• N/A	• N/A	N/A
N/A	• N/A	• N/A	N/A
N/A	• N/A	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 486: Proof of IF adherence to VRPS3 for VM5

VRPS3		VM5	
IF	Parameterization		IF
N/A	• N/A	• N/A	N/A
N/A	• N/A	• N/A	N/A
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.3.6 VM6 defined from VRPS3

Table 487 provides the mapping between IoX with parameterization where applicable and Table 488 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 487: Proof of IoX adherence to VRPS3 for VM6

VRPS3		VM6	
IoX	Parameterization		IoX
N/A	• N/A	• Force: 0.5 N	Off-command
N/A	• N/A	• Force: 0.5 N	On-command
N/A	• N/A	• Lumen: <0.5 lm	No-light

N/A	• N/A	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 488: Proof of IF adherence to VRPS3 for VM6

VRPS3		VM6	
IF	Parameterization		IF
N/A	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
N/A	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• N/A	N/A

A.11.3.7 VM7 defined from VRPS3

Table 489 provides the mapping between IoX with parameterization where applicable and Table 490 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 489: Proof of IoX adherence to VRPS3 for VM7

VRPS3		VM7	
IoX	Parameterization		IoX
N/A	• N/A	• N/A	0
N/A	• N/A	• N/A	1
N/A	• N/A	• N/A	0
N/A	• N/A	• N/A	1
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 490: Proof of IF adherence to VRPS3 for VM7

VRPS3		VM7	
IF	Parameterization		IF
N/A	• N/A	• N/A	Input IF
N/A	• N/A	• N/A	Output IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• N/A	N/A

A.11.3.8 VM8 defined from VRPS3

Table 491 provides the mapping between IoX with parameterization where applicable and Table 492 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 491: Proof of IoX adherence to VRPS3 for VM8

VRPS3		VM8	
IoX	Parameterization		IoX
N/A	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
N/A	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command
N/A	• N/A	• Lumen: <0.5 lm	No-light
N/A	• N/A	• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light
Water	• Pressure: 1-5 atm	• N/A	N/A

	• Humidity: 0-100%		

Table 492: Proof of IF adherence to VRPS3 for VM8

VRPS3		VM8	
IF	Parameterization		IF
N/A	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
N/A	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• N/A	N/A

A.11.3.9 VM9 defined from VRPS3

Table 493 provides the mapping between IoX with parameterization where applicable and Table 494 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 493: Proof of IoX adherence to VRPS3 for VM9

VRPS3		VM9	
IoX	Parameterization		IoX
N/A	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
N/A	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1

		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
N/A	• N/A	• Lumen: <0.5 lm	No-light
N/A	• N/A	• Wavelength: 590 nm [blue] • Lumen: 250 lm	Blue-light 1
		• Wavelength: 590 nm [blue] • Lumen: 750 lm	Blue-light 2
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 494: Proof of IF adherence to VRPS3 for VM9

VRPS3		VM9	
IF	Parameterization		IF
N/A	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
N/A	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• N/A	N/A

A.11.3.10 VM10 defined from VRPS3

Table 495 provides the mapping between IoX with parameterization where applicable and Table 496 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 495: Proof of IoX adherence to VRPS3 for VM10

VRPS3		VM10	
IoX	Parameterization		IoX
N/A	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Green to Red
N/A	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	Red to Green
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	Green to Blue
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	Blue to Green
N/A	• N/A	• Wavelength: 650 nm [red]	Red Ink
N/A	• N/A	• Wavelength: 510 nm [green]	Green Ink
		• Wavelength: 475 nm [blue]	Blue Ink
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 496: Proof of IF adherence to VRPS3 for VM10

VRPS3		VM10	
IF	Parameterization		IF
N/A	• N/A	• Diameter: 5 mm • Material: black plastic	Color Change IF
N/A	• N/A	• Diameter: 2 mm • Material: brass	Ink IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• N/A	N/A

A.11.3.11 VM11 defined from VRPS3

Table 497 provides the mapping between IoX with parameterization where applicable and Table 498 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 497: Proof of IoX adherence to VRPS3 for VM11

VRPS3		VM11	
IoX	Parameterization		IoX
N/A	• N/A	• N/A	Cold
N/A	• N/A	• N/A	Hot
N/A	• N/A	• N/A	No delicious smell
N/A	• N/A	• N/A	Delicious
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 498: Proof of IF adherence to VRPS3 for VM11

VRPS3		VM11	
IF	Parameterization		IF
N/A	• N/A	• N/A	Oven IF
N/A	• N/A	• N/A	Kitchen Air IF
Water IF	• Volume: 12k-15k mm^3	• N/A	N/A

	• Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic		

A.11.3.12 VM12 defined from VRPS3

Table 499 provides the mapping between IoX with parameterization where applicable and Table 500 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 499: Proof of IoX adherence to VRPS3 for VM12

VRPS3		VM12	
IoX	Parameterization		IoX
N/A	• N/A	• N/A	Off-trigger
N/A	• N/A	• N/A	On-trigger
N/A	• N/A	• Lumen: <0.5 lm	No-light
N/A	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 500: Proof of IF adherence to VRPS3 for VM12

VRPS3		VM12	
IF	Parameterization		IF
N/A	• N/A	• N/A	Trigger IF
N/A	• N/A	• N/A	Light IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• N/A	N/A

A.11.3.13 VM13 defined from VRPS3

Table 501 provides the mapping between IoX with parameterization where applicable and Table 502 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 501: Proof of IoX adherence to VRPS3 for VM13

VRPS3		VM13	
IoX	Parameterization		IoX
N/A	• N/A	• N/A	Off-command
N/A	• N/A	• N/A	On-command
N/A	• N/A	• Lumen: <0.5	Radio-off
N/A	• N/A	• N/A	Radio-on
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 502: Proof of IF adherence to VRPS3 for VM13

VRPS3		VM13	
IF	Parameterization		IF
N/A	• N/A	• N/A	Off IF
N/A	• N/A	• N/A	Radio Display IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• N/A	N/A

A.11.3.14 VM14 defined from VRPS3

Table 503 provides the mapping between IoX with parameterization where applicable and Table 504 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 503: Proof of IoX adherence to VRPS3 for VM14

VRPS3		VM14	
IoX	Parameterization		IoX

N/A	• N/A	• N/A	N/A
N/A	• N/A	• N/A	N/A
N/A	• N/A	• N/A	N/A
N/A	• N/A	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: -5-1000 atm • Humidity: 0-100%	Water

Table 504: Proof of IF adherence to VRPS3 for VM14

VRPS3		VM14	
IF	Parameterization		IF
N/A	• N/A	• N/A	N/A
N/A	• N/A	• N/A	N/A
Water IF	• N/A	• N/A	Water IF

A.11.3.15 VM15 defined from VRPS3

Table 505 provides the mapping between IoX with parameterization where applicable and Table 506 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 505: Proof of IoX adherence to VRPS3 for VM15

VRPS3		VM15	
IoX	Parameterization		IoX
N/A	• N/A	• N/A	N/A
N/A	• N/A	• N/A	N/A
N/A	• N/A	• N/A	N/A
N/A	• N/A	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 506: Proof of IF adherence to VRPS3 for VM15

VRPS3		VM15	
IF	Parameterization		IF
N/A	• N/A	• N/A	N/A
N/A	• N/A	• N/A	N/A
Water IF	• Volume: 12k-15k mm^3	• N/A	Water IF

	• Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic		

A.11.3.16 VM16 defined from VRPS3

Table 507 provides the mapping between IoX with parameterization where applicable and Table 508 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 507: Proof of IoX adherence to VRPS3 for VM16

VRPS3		VM16	
IoX	Parameterization		IoX
N/A	• N/A	• N/A	Off-trigger
N/A	• N/A	• N/A	On-trigger
N/A	• N/A	• Lumen: <0.5 lm	No-light
N/A	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 508: Proof of IF adherence to VRPS3 for VM16

VRPS3		VM16	
IF	Parameterization		IF
N/A	• N/A	• N/A	Trigger IF
N/A	• N/A	• N/A	Light IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• N/A	N/A

A.11.3.17 VM17 defined from VRPS3

Table 509 provides the mapping between IoX with parameterization where applicable and Table 510 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 509: Proof of IoX adherence to VRPS3 for VM17

VRPS3		VM17	
IoX	Parameterization		IoX
N/A	• N/A	• N/A	Off-command
N/A	• N/A	• N/A	On-command
N/A	• N/A	• Lumen: <0.5	Radio-off
N/A	• N/A	• N/A	Radio-on
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 510: Proof of IF adherence to VRPS3 for VM17

VRPS3		VM17	
IF	Parameterization		IF
N/A	• N/A	• N/A	Trigger IF
N/A	• N/A	• N/A	Light IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• N/A	Water IF

A.11.3.18 VM18 defined from VRPS3

Table 511 provides the mapping between IoX with parameterization where applicable and Table 512 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S7, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 511: Proof of IoX adherence to VRPS3 for VM18

VRPS3		VM18	
IoX	Parameterization		IoX

N/A	• N/A	• N/A	Off-command
N/A	• N/A	• N/A	On-command
N/A	• N/A	• Lumen: <0.5 lm	No-light
N/A	• N/A	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: -5-1,000 atm • Humidity: 0-100%	Water

Table 512: Proof of IF adherence to VRPS3 for VM18

VRPS3		VM18	
IF	Parameterization		IF
N/A	• N/A	• N/A	On/off IF
N/A	• N/A	• N/A	Light IF
Water IF	• Volume: 12k-15k mm^3 • Diameter: 40-60 mm • Length: 225-260 mm • Material: black plastic	• N/A	Water IF

A.11.4 VM defined from VRPS4

A.11.4.1 VM1 defined from VRPS4

Table 513 provides the mapping between IoX with parameterization where applicable and Table 514 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 513: Proof of IoX adherence to VRPS4 for VM1

VRPS4		VM1	
IoX	Parameterization		IoX
Off-command	• N/A	• Force: 0.5 N	Off-command
On-command	• N/A	• Force: 0.5 N	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light	• Wavelength: 450-495 nm [blue]	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light

	• Lumen: 200-1,000 lm		
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 514: Proof of IF adherence to VRPS4 for VM1

VRPS4		VM1	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.4.2 VM2 defined from VRPS4

Table 515 provides the mapping between IoX with parameterization where applicable and Table 516 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 515: Proof of IoX adherence to VRPS4 for VM2

VRPS4		VM2	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees	On-command 1

		• Direction: counter-clockwise	
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
N/A	• N/A	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 516: Proof of IF adherence to VRPS4 for VM2

VRPS4		VM2	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

A.11.4.3 VM3 defined from VRPS4

Table 517 provides the mapping between IoX with parameterization where applicable and Table 518 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 517: Proof of IoX adherence to VRPS4 for VM3

VRPS4		VM3	
IoX	Parameterization		IoX
Off-command	• N/A	• Force: 0.5 N	Off-command
On-command	• N/A	• Force: 0.5 N	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 518: Proof of IF adherence to VRPS4 for VM3

VRPS4		VM3	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.4.4 VM4 defined from VRPS4

Table 519 provides the mapping between IoX with parameterization where applicable and Table 520 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has

been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 519: Proof of IoX adherence to VRPS4 for VM4

VRPS4		VM4	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
N/A	• N/A	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 520: Proof of IF adherence to VRPS4 for VM4

VRPS4		VM4	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 12,800 mm • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

A.11.4.5 VM5 defined from VRPS4

Table 521 provides the mapping between IoX with parameterization where applicable and Table 522 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 521: Proof of IoX adherence to VRPS4 for VM5

VRPS4		VM5	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	N/A
On-command	• N/A	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• N/A	N/A
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 522: Proof of IF adherence to VRPS4 for VM5

VRPS4		VM5	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	N/A

Light IF	• N/A	• N/A	N/A
N/A	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.4.6 VM6 defined from VRPS4

Table 523 provides the mapping between IoX with parameterization where applicable and Table 524 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 523: Proof of IoX adherence to VRPS4 for VM6

VRPS4		VM6	
IoX	Parameterization		IoX
Off-command	• N/A	• Force: 0.5 N	Off-command
On-command	• N/A	• Force: 0.5 N	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• N/A	N/A

Table 524: Proof of IF adherence to VRPS4 for VM6

VRPS4		VM6	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• N/A	N/A

A.11.4.7 VM7 defined from VRPS4

Table 525 provides the mapping between IoX with parameterization where applicable and Table 526 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has

been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 525: Proof of IoX adherence to VRPS4 for VM7

VRPS4		VM7	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	0
On-command	• N/A	• N/A	1
No-light	• Lumen: <0.5 lm	• N/A	0
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• N/A	1
N/A	• N/A	• N/A	N/A

Table 526: Proof of IF adherence to VRPS4 for VM7

VRPS4		VM7	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Input IF
Light IF	• N/A	• N/A	Output IF
N/A	• N/A	• N/A	N/A

A.11.4.8 VM8 defined from VRPS4

Table 527 provides the mapping between IoX with parameterization where applicable and Table 528 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 527: Proof of IoX adherence to VRPS4 for VM8

VRPS4		VM8	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees	On-command

		• Direction: counter-clockwise	
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light
N/A	• N/A	• N/A	N/A

Table 528: Proof of IF adherence to VRPS4 for VM8

VRPS4		VM8	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• N/A	N/A

A.11.4.9 VM9 defined from VRPS4

Table 529 provides the mapping between IoX with parameterization where applicable and Table 530 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. Furthermore, the VM does adhere to the VRPS instantiation of the PSF. Therefore, the VM can be defined on the basis of this VRPS.

Table 529: Proof of IoX adherence to VRPS4 for VM9

VRPS4		VM9	
IoX	Parameterization		IoX
Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1

		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Blue-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Blue-light 2
N/A	• N/A	• N/A	N/A

Table 530: Proof of IF adherence to VRPS4 for VM9

VRPS4		VM9	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
N/A	• N/A	• N/A	N/A

A.11.4.10 VM10 defined from VRPS4

Table 531 provides the mapping between IoX with parameterization where applicable and Table 532 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 531: Proof of IoX adherence to VRPS4 for VM10

VRPS4		VM10	
IoX	Parameterization		IoX

Off-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Green to Red
On-command	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	Red to Green
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	Green to Blue
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	Blue to Green
No-light	• Lumen: <0.5 lm	• Wavelength: 650 nm [red]	Red Ink
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• Wavelength: 510 nm [green]	Green Ink
		• Wavelength: 475 nm [blue]	Blue Ink
N/A	• N/A	• N/A	N/A

Table 532: Proof of IF adherence to VRPS4 for VM10

VRPS4		VM10	
IF	Parameterization		IF
On/off IF	• N/A	• Diameter: 5 mm • Material: black plastic	Color Change IF
Light IF	• N/A	• Diameter: 2 mm • Material: brass	Ink IF
N/A	• N/A	• N/A	N/A

A.11.4.11 VM11 defined from VRPS4

Table 533 provides the mapping between IoX with parameterization where applicable and Table 534 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 533: Proof of IoX adherence to VRPS4 for VM11

VRPS4		VM11	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Cold
On-command	• N/A	• N/A	Hot
No-light	• Lumen: <0.5 lm	• N/A	No delicious smell
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• N/A	Delicious
N/A	• N/A	• N/A	N/A

Table 534: Proof of IF adherence to VRPS4 for VM11

VRPS4		VM11	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Oven IF
Light IF	• N/A	• N/A	Kitchen Air IF
N/A	• N/A	• N/A	N/A

A.11.4.12 VM12 defined from VRPS4

Table 535 provides the mapping between IoX with parameterization where applicable and Table 536 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 535: Proof of IoX adherence to VRPS4 for VM12

VRPS4		VM12	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-trigger
On-command	• N/A	• N/A	On-trigger
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light	• Wavelength: 450-495 nm [blue]	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light

	• Lumen: 200-1,000 lm		
N/A	• N/A	• N/A	N/A

Table 536: Proof of IF adherence to VRPS4 for VM12

VRPS4		VM12	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Trigger IF
Light IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	N/A

A.11.4.13 VM13 defined from VRPS4

Table 537 provides the mapping between IoX with parameterization where applicable and Table 538 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 537: Proof of IoX adherence to VRPS4 for VM13

PSF for VRPS4		VM13	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-command
On-command	• N/A	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-off
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• N/A	Radio-on
N/A	• N/A	• N/A	N/A

Table 538: Proof of IF adherence to VRPS4 for VM13

VRPS4		VM13	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Off IF
Light IF	• N/A	• N/A	Radio Display IF
N/A	• N/A	• N/A	N/A

A.11.4.14 VM14 defined from VRPS4

Table 539 provides the mapping between IoX with parameterization where applicable and Table 540 provides the mapping between IF with parameterization where applicable. The

VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 539: Proof of IoX adherence to VRPS4 for VM14

VRPS4		VM14	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	N/A
On-command	• N/A	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• N/A	N/A
N/A	• N/A	• Pressure: -5-1000 atm • Humidity: 0-100%	Water

Table 540: Proof of IF adherence to VRPS4 for VM14

VRPS4		VM14	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	N/A
Light IF	• N/A	• N/A	N/A
N/A	• N/A	• N/A	Water IF

A.11.4.15 VM15 defined from VRPS4

Table 541 provides the mapping between IoX with parameterization where applicable and Table 542 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 541: Proof of IoX adherence to VRPS4 for VM15

VRPS4		VM15	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	N/A
On-command	• N/A	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Blue-light	• Wavelength: 450-495 nm [blue]	• N/A	N/A

	• Lumen: 200-1,000 lm		
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 542: Proof of IF adherence to VRPS4 for VM15

VRPS4		VM15	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	N/A
Light IF	• N/A	• N/A	N/A
N/A	• N/A	• N/A	Water IF

A.11.4.16 VM16 defined from VRPS4

Table 543 provides the mapping between IoX with parameterization where applicable and Table 544 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 543: Proof of IoX adherence to VRPS4 for VM16

VRPS4		VM16	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-trigger
On-command	• N/A	• N/A	On-trigger
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 544: Proof of IF adherence to VRPS4 for VM16

VRPS4		VM16	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Trigger IF
Light IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	N/A

A.11.4.17 VM17 defined from VRPS4

Table 545 provides the mapping between IoX with parameterization where applicable and Table 546 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 545: Proof of IoX adherence to VRPS4 for VM17

VRPS4		VM17	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-command
On-command	• N/A	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-off
Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• N/A	Radio-on
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 546: Proof of IF adherence to VRPS4 for VM17

VRPS4		VM17	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	Trigger IF
Light IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	Water IF

A.11.4.18 VM18 defined from VRPS4

Table 547 provides the mapping between IoX with parameterization where applicable and Table 548 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 547: Proof of IoX adherence to VRPS4 for VM18

VRPS4		VM18	
IoX	Parameterization		IoX
Off-command	• N/A	• N/A	Off-command
On-command	• N/A	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light

Blue-light	• Wavelength: 450-495 nm [blue] • Lumen: 200-1,000 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• Pressure: -5-1,000 atm • Humidity: 0-100%	Water

Table 548: Proof of IF adherence to VRPS4 for VM18

VRPS4		VM18	
IF	Parameterization		IF
On/off IF	• N/A	• N/A	On/off IF
Light IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	Water IF

A.11.5 VM defined from VRPS5

A.11.5.1 VM1 defined from VRPS5

Table 549 provides the mapping between IoX with parameterization where applicable and Table 550 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 549: Proof of IoX adherence to VRPS5 for VM1

VRPS5		VM1	
IoX	Parameterization		IoX
0	• N/A	• Force: 0.5 N	Off-command
1	• N/A	• Force: 0.5 N	On-command
0	• N/A	• Lumen: <0.5 lm	No-light
1	• N/A	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 550: Proof of IF adherence to VRPS5 for VM1

VRPS5		VM1	
IF	Parameterization		IF
Input IF	• N/A	• Diameter: 15 mm	On/off IF

		• Material: black rubber	
Output IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.5.2 VM2 defined from VRPS5

Table 551 provides the mapping between IoX with parameterization where applicable and Table 552 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 551: Proof of IoX adherence to VRPS5 for VM2

VRPS5		VM2	
IoX	Parameterization		IoX
0	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
1	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees	On-command 3

		• Direction: clockwise	
0	• N/A	• Lumen: <0.5 lm	No-light
1	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
N/A	• N/A	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 552: Proof of IF adherence to VRPS5 for VM2

VRPS5		VM2	
IF	Parameterization		IF
Input IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Output IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

A.11.5.3 VM3 defined from VRPS5

Table 533 provides the mapping between IoX with parameterization where applicable and Table 534 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 553: Proof of IoX adherence to VRPS5 for VM3

VRPS5		VM3	
IoX	Parameterization		IoX
0	• N/A	• Force: 0.5 N	Off-command
1	• N/A	• Force: 0.5 N	On-command

0	• N/A	• Lumen: <0.5 lm	No-light
1	• N/A	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 554: Proof of IF adherence to VRPS5 for VM3

VRPS5		VM3	
IF	Parameterization		IF
Input IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Output IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.5.4 VM4 defined from VRPS5

Table 555 provides the mapping between IoX with parameterization where applicable and Table 556 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 555: Proof of IoX adherence to VRPS5 for VM4

VRPS5		VM4	
IoX	Parameterization		IoX
0	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
1	• N/A	• Torque: 0.5 Nm • Rotation: roll	On-command 1

		• Position(s): 120 degrees • Direction: counter-clockwise	
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
0	• N/A	• Lumen: <0.5 lm	No-light
1	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
N/A	• N/A	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 556: Proof of IF adherence to VRPS5 for VM4

VRPS5		VM4	
IF	Parameterization		IF
Input IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Output IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
N/A	• N/A	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

A.11.5.5 VM5 defined from VRPS5

Table 557 provides the mapping between IoX with parameterization where applicable and Table 558 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 557: Proof of IoX adherence to VRPS5 for VM5

VRPS5		VM5	
IoX	Parameterization		IoX
0	• N/A	• N/A	N/A
1	• N/A	• N/A	N/A
0	• N/A	• N/A	N/A
1	• N/A	• N/A	N/A
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 558: Proof of IF adherence to VRPS5 for VM5

VRPS5		VM5	
IF	Parameterization		IF
Input IF	• N/A	• N/A	N/A
Output IF	• N/A	• N/A	N/A
N/A	• N/A	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.11.5.6 VM6 defined from VRPS5

Table 559 provides the mapping between IoX with parameterization where applicable and Table 560 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 559: Proof of IoX adherence to VRPS5 for VM6

VRPS5		VM6	
IoX	Parameterization		IoX

0	• N/A	• Force: 0.5 N	Off-command
1	• N/A	• Force: 0.5 N	On-command
0	• N/A	• Lumen: <0.5 lm	No-light
1	• N/A	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• N/A	N/A

Table 560: Proof of IF adherence to VRPS5 for VM6

VRPS5		VM6	
IF	Parameterization		IF
Input IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Output IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• N/A	N/A

A.11.5.7 VM7 defined from VRPS5

Table 561 provides the mapping between IoX with parameterization where applicable and Table 562 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 561: Proof of IoX adherence to VRPS5 for VM7

VRPS5		VM7	
IoX	Parameterization		IoX
0	• N/A	• N/A	0
1	• N/A	• N/A	1
0	• N/A	• N/A	0
1	• N/A	• N/A	1
N/A	• N/A	• N/A	N/A

Table 562: Proof of IF adherence to VRPS5 for VM7

VRPS5		VM7	
IF	Parameterization		IF
Input IF	• N/A	• N/A	Input IF
Output IF	• N/A	• N/A	Output IF
N/A	• N/A	• N/A	N/A

A.11.5.8 VM8 defined from VRPS5

Table 563 provides the mapping between IoX with parameterization where applicable and Table 564 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 563: Proof of IoX adherence to VRPS5 for VM8

VRPS5		VM8	
IoX	Parameterization		IoX
0	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
1	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command
0	• N/A	• Lumen: <0.5 lm	No-light
1	• N/A	• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light
N/A	• N/A	• N/A	N/A

Table 564: Proof of IF adherence to VRPS5 for VM8

VRPS5		VM8	
IF	Parameterization		IF
Input IF	• N/A	• Diameter: 15 mm • Material: black rubber	On/off IF
Output IF	• N/A	• Diameter: 57 mm • Material: clear plastic	Light IF
N/A	• N/A	• N/A	N/A

A.11.5.9 VM9 defined from VRPS5

Table 565 provides the mapping between IoX with parameterization where applicable and Table 566 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 565: Proof of IoX adherence to VRPS5 for VM9

VRPS5		VM9	
IoX	Parameterization		IoX
0	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
1	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
0	• N/A	• Lumen: <0.5 lm	No-light
1	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Blue-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Blue-light 2
N/A	• N/A	• N/A	N/A

Table 566: Proof of IF adherence to VRPS5 for VM9

VRPS5		VM9	
IF	Parameterization		IF
Input IF	• N/A	• Diameter: 50 mm • Material: black plastic	On/off IF
Output IF	• N/A	• Diameter: 45 mm • Material: clear plastic	Light IF
N/A	• N/A	• N/A	N/A

A.11.5.10 VM10 defined from VRPS5

Table 567 provides the mapping between IoX with parameterization where applicable and Table 568 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 567: Proof of IoX adherence to VRPS5 for VM10

VRPS5		VM10	
IoX	Parameterization		IoX
0	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Green to Red
1	• N/A	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	Red to Green
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	Green to Blue
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees	Blue to Green

		• Direction: clockwise	
0	• N/A	• Wavelength: 650 nm [red]	Red Ink
1	• N/A	• Wavelength: 510 nm [green]	Green Ink
		• Wavelength: 475 nm [blue]	Blue Ink
N/A	• N/A	• N/A	N/A

Table 568: Proof of IF adherence to VRPS5 for VM10

VRPS5		VM10	
IF	Parameterization		IF
Input IF	• N/A	• Diameter: 5 mm • Material: black plastic	Color Change IF
Output IF	• N/A	• Diameter: 2 mm • Material: brass	Ink IF
N/A	• N/A	• N/A	N/A

A.11.5.11 VM11 defined from VRPS5

Table 569 provides the mapping between IoX with parameterization where applicable and Table 570 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is symbolically changed to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 569: Proof of IoX adherence to VRPS5 for VM11

VRPS5		VM11	
IoX	Parameterization		IoX
0	• N/A	• N/A	Cold
1	• N/A	• N/A	Hot
0	• N/A	• N/A	No delicious smell
1	• N/A	• N/A	Delicious
N/A	• N/A	• N/A	N/A

Table 570: Proof of IF adherence to VRPS5 for VM11

VRPS5		VM11	
IF	Parameterization		IF
Input IF	• N/A	• N/A	Oven IF
Output IF	• N/A	• N/A	Kitchen Air IF

N/A	• N/A	• N/A	N/A

A.11.5.12 VM12 defined from VRPS5

Table 571 provides the mapping between IoX with parameterization where applicable and Table 572 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 571: Proof of IoX adherence to VRPS5 for VM12

VRPS5		VM12	
IoX	Parameterization		IoX
0	• N/A	• N/A	Off-trigger
1	• N/A	• N/A	On-trigger
0	• N/A	• Lumen: <0.5 lm	No-light
1	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
N/A	• N/A	• N/A	N/A

Table 572: Proof of IF adherence to VRPS5 for VM12

VRPS5		VM12	
IF	Parameterization		IF
Input IF	• N/A	• N/A	Trigger IF
Output IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	N/A

A.11.5.13 VM13 defined from VRPS5

Table 573 provides the mapping between IoX with parameterization where applicable and Table 574 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 573: Proof of IoX adherence to VRPS5 for VM13

VRPS5		VM13	
IoX	Parameterization		IoX
0	• N/A	• N/A	Off-command
1	• N/A	• N/A	On-command
0	• N/A	• Lumen: <0.5	Radio-off
1	• N/A	• N/A	Radio-on

N/A	• N/A	• N/A	N/A

Table 574: Proof of IF adherence to VRPS5 for VM13

VRPS5		VM13	
IF	Parameterization		IF
Input IF	• N/A	• N/A	Off IF
Output IF	• N/A	• N/A	Radio Display IF
N/A	• N/A	• N/A	N/A

A.11.5.14 VM14 defined from VRPS5

Table 575 provides the mapping between IoX with parameterization where applicable and Table 576 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 575: Proof of IoX adherence to VRPS5 for VM14

VRPS5		VM14	
IoX	Parameterization		IoX
0	• N/A	• N/A	N/A
1	• N/A	• N/A	N/A
0	• N/A	• N/A	N/A
1	• N/A	• N/A	N/A
N/A	• N/A	• Pressure: -5-1000 atm • Humidity: 0-100%	Water

Table 576: Proof of IF adherence to VRPS5 for VM14

VRPS5		VM14	
IF	Parameterization		IF
Input IF	• N/A	• N/A	N/A
Output IF	• N/A	• N/A	N/A
N/A	• N/A	• N/A	Water IF

A.11.5.15 VM15 defined from VRPS5

Table 577 provides the mapping between IoX with parameterization where applicable and Table 578 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has

been proven to not adhere to. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 577: Proof of IoX adherence to VRPS5 for VM15

VRPS5		VM15	
IoX	Parameterization		IoX
0	• N/A	• N/A	N/A
1	• N/A	• N/A	N/A
0	• N/A	• N/A	N/A
1	• N/A	• N/A	N/A
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 578: Proof of IF adherence to VRPS5 for VM15

VRPS5		VM15	
IF	Parameterization		IF
Input IF	• N/A	• N/A	N/A
Output IF	• N/A	• N/A	N/A
N/A	• N/A	• N/A	Water IF

A.11.5.16 VM16 defined from VRPS5

Table 579 provides the mapping between IoX with parameterization where applicable and Table 580 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 579: Proof of IoX adherence to VRPS5 for VM16

VRPS5		VM16	
IoX	Parameterization		IoX
0	• N/A	• N/A	Off-trigger
1	• N/A	• N/A	On-trigger
0	• N/A	• Lumen: <0.5 lm	No-light
1	• N/A	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 580: Proof of IF adherence to VRPS5 for VM16

VRPS5		VM16	
IF	Parameterization		IF
Input IF	• N/A	• N/A	Trigger IF
Output IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	N/A

A.11.5.17 VM17 defined from VRPS5

Table 581 provides the mapping between IoX with parameterization where applicable and Table 582 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 581: Proof of IoX adherence to VRPS5 for VM17

VRPS5		VM17	
IoX	Parameterization		IoX
0	• N/A	• N/A	Off-command
1	• N/A	• N/A	On-command
0	• N/A	• Lumen: <0.5	Radio-off
1	• N/A	• N/A	Radio-on
N/A	• N/A	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 582: Proof of IF adherence to VRPS5 for VM17

VRPS5		VM17	
IF	Parameterization		IF
Input IF	• N/A	• N/A	Trigger IF
Output IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	Water IF

A.11.5.18 VM18 defined from VRPS5

Table 583 provides the mapping between IoX with parameterization where applicable and Table 584 provides the mapping between IF with parameterization where applicable. The VRPS is based on PSF_S2, for which the SM that is parameterized to form the VM has been proven to adhere to. However, the VM does not adhere to the VRPS instantiation of the PSF. Therefore, the VM cannot be defined on the basis of this VRPS.

Table 583: Proof of IoX adherence to VRPS5 for VM18

VRPS5		VM18	

IoX	Parameterization		IoX
0	• N/A	• N/A	Off-command
1	• N/A	• N/A	On-command
0	• N/A	• Lumen: <0.5 lm	No-light
1	• N/A	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
N/A	• N/A	• Pressure: -5-1,000 atm • Humidity: 0-100%	Water

Table 584: Proof of IF adherence to VRPS5 for VM18

VRPS5		VM18	
IF	Parameterization		IF
Input IF	• N/A	• N/A	On/off IF
Output IF	• N/A	• N/A	Light IF
N/A	• N/A	• N/A	Water IF

A.12 Supporting results from VM defined from SD

A.12.1 Supporting results of VM defined from SD1

A.12.1.1 VM1 definition from SD1

Because the VM is a SD and the two are specified at L1, the two are said to have an identity isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

A.12.1.2 VM2 definition from SD1

Table 585 provides the mapping between IoX with parameterization where applicable and Table 586 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 585: Proof of IoX morphic equivalence between SD1 for VM2

SD1		VM2	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command

On-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-6 atm • Humidity: 0-100%	Water

Table 586: Proof of IF morphic equivalence between SD1 for VM2

SD1		VM2	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm	Water IF

	• Material: black plastic	• Material: black plastic	

A.12.1.3 VM3 definition from SD1

Table 587 provides the mapping between IoX with parameterization where applicable and Table 588 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have an identity isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 587: Proof of IoX morphic equivalence between SD1 for VM3

SD1		VM3	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Force: 0.5 N	Off-command
On-command	• Force: 0.5 N	• Force: 0.5 N	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%N/A	Water
N/A	• N/A	• Voltage: <0.01 V	No-power
N/A	• N/A	• Voltage: 3 V	Power

Table 588: Proof of IF morphic equivalence between SD1 for VM3

SD1		VM3	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
N/A	• N/A	• Material: black plastic	Power IF

A.12.1.4 VM4 definition from SD1

Table 589 provides the mapping between IoX with parameterization where applicable and Table 590 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 589: Proof of IoX morphic equivalence between SD1 for VM4

SD1		VM4	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Blue-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Blue-light 2

Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Voltage: <0.01V	Water
N/A	• N/A	• Voltage: 1.5V	No-power
N/A	• N/A	• Voltage: 3V	Power 1
N/A	• N/A	• Pressure: 1-6 atm • Humidity: 0-100%	Power 2

Table 590: Proof of IF morphic equivalence between SD1 for VM4

SD1		VM4	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	N/A
N/A	• N/A	• Diameter: 50 mm • Material: black plastic	Power IF

A.12.1.5 VM5 definition from SD1

Table 591 provides the mapping between IoX with parameterization where applicable and Table 592 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S7 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S7.

Table 591: Proof of IoX morphic equivalence between SD1 for VM5

SD1		VM5	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	N/A
On-command	• Force: 0.5 N	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A

Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 592: Proof of IF morphic equivalence between SD1 for VM5

SD1		VM5	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	N/A
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	N/A
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.12.1.6 VM6 definition from SD1

Table 593 provides the mapping between IoX with parameterization where applicable and Table 594 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 593: Proof of IoX morphic equivalence between SD1 for VM6

SD1		VM6	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Force: 0.5 N	Off-command
On-command	• Force: 0.5 N	• Force: 0.5 N	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm	• N/A	N/A

	• Humidity: 0-100%		
N/A	• N/A	• Voltage: <0.01 V	No-power
N/A	• N/A	• Voltage: 3 V	Power

Table 594: Proof of IF morphic equivalence between SD1 for VM6

SD1		VM6	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
N/A	• N/A	• Material: black plastic	Power IF

A.12.1.7 VM7 definition from SD1

Table 595 provides the mapping between IoX with parameterization where applicable and Table 596 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to remain a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 due to the lack of parameterization of the VM.

Table 595: Proof of IoX morphic equivalence between SD1 for VM7

SD1		VM7	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	0
On-command	• Force: 0.5 N	• N/A	1
No-light	• Lumen: <0.5 lm	• N/A	0
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	1
Water	• Pressure: 1-5 atm	• N/A	N/A

	• Humidity: 0-100%		

Table 596: Proof of IF morphic equivalence between SD1 for VM7

SD1		VM7	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Input IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Output IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A

A.12.1.8 VM8 definition from SD1

Table 597 provides the mapping between IoX with parameterization where applicable and Table 598 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 597: Proof of IoX morphic equivalence between SD1 for VM8

SD1		VM8	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command

No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A
N/A	• N/A	• Voltage: <0.01 V	No-power
N/A	• N/A	• Voltage: 5 V	Power

Table 598: Proof of IF morphic equivalence between SD1 for VM8

SD1		VM8	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
N/A	• N/A	• Material: black plastic	Power IF

A.12.1.9 VM9 definition from SD1

Table 599 provides the mapping between IoX with parameterization where applicable and Table 600 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 599: Proof of IoX morphic equivalence between SD1 for VM9

SD1		VM9	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll	Off-command

		• Position: 0 degrees • Direction: clockwise	
On-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 475 nm [blue] • Lumen: 200 lm	Blue-light 1
		• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light 2
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-6 atm • Humidity: 0-100%	Water
N/A	• N/A	• Voltage: <0.01V	No-power
N/A	• N/A	• Voltage: 1V	Power 1
N/A	• N/A	• Voltage: 2V	Power 2

Table 600: Proof of IF morphic equivalence between SD1 for VM9

SD1		VM9	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• Diameter: 57 mm	• Diameter: 45 mm	Light IF

	• Material: clear plastic	• Material: clear plastic	
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
N/A	• N/A	• Material: black plastic	Power IF

A.12.1.10 VM10 definition from SD1

Table 601 provides the mapping between IoX with parameterization where applicable and Table 602 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 601: Proof of IoX morphic equivalence between SD1 for VM10

SD1		VM10	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Green to Red
On-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	Red to Green
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	Green to Blue
		• Torque: 0.5 Nm • Rotation: roll	Blue to Green

		• Position(s): 120 degrees • Direction: clockwise	
No-light	• Lumen: <0.5 lm	• Wavelength: 650 nm [red]	Red Ink
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 510 nm [green]	Green Ink
		• Wavelength: 475 nm [blue]	Blue Ink
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 602: Proof of IF morphic equivalence between SD1 for VM10

SD1		VM10	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 5 mm • Material: black plastic	Color Change IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 2 mm • Material: brass	Ink IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A

A.12.1.11 VM11 definition from SD1

Table 603 provides the mapping between IoX with parameterization where applicable and Table 604 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to remain a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 due to the lack of parameterization of the VM.

Table 603: Proof of IoX morphic equivalence between SD1 for VM11

SD1		VM11	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	Cold
On-command	• Force: 0.5 N	• N/A	Hot

No-light	• Lumen: <0.5 lm	• N/A	No delicious smell
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	Delicious
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 604: Proof of IF morphic equivalence between SD1 for VM11

SD1		VM11	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Oven IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Kitchen Air IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A

A.12.1.12 VM12 definition from SD1

Table 605 provides the mapping between IoX with parameterization where applicable and Table 606 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 605: Proof of IoX morphic equivalence between SD1 for VM12

SD1		VM12	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	Off-trigger
On-command	• Force: 0.5 N	• N/A	On-trigger
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
Water	• Pressure: 1-5 atm	• N/A	N/A

	• Humidity: 0-100%		

Table 606: Proof of IF morphic equivalence between SD1 for VM12

SD1		VM12	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Trigger IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A

A.12.1.13 VM13 definition from SD1

Table 607 provides the mapping between IoX with parameterization where applicable and Table 608 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 607: Proof of IoX morphic equivalence between SD1 for VM13

SD1		VM13	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	Off-command
On-command	• Force: 0.5 N	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-off
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	Radio-on
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A

Table 608: Proof of IF morphic equivalence between SD1 for VM13

SD1		VM13	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Radio Display IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A

A.12.1.14 VM14 definition from SD1

Table 609 provides the mapping between IoX with parameterization where applicable and Table 610 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S7 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S7.

Table 609: Proof of IoX morphic equivalence between SD1 for VM14

SD1		VM14	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	N/A
On-command	• Force: 0.5 N	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: -5-1000 atm • Humidity: 0-100%	Water

Table 610: Proof of IF morphic equivalence between SD1 for VM14

SD1		VM14	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm	• N/A	N/A

	• Material: black rubber		
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	N/A
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF

A.12.1.15 VM15 definition from SD1

Table 611 provides the mapping between IoX with parameterization where applicable and Table 612 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S7 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S7.

Table 611: Proof of IoX morphic equivalence between SD1 for VM15

SD1		VM15	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	N/A
On-command	• Force: 0.5 N	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 612: Proof of IF morphic equivalence between SD1 for VM15

SD1		VM15	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	N/A
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	N/A

Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF

A.12.1.16 VM16 definition from SD1

Table 613 provides the mapping between IoX with parameterization where applicable and Table 614 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 613: Proof of IoX morphic equivalence between SD1 for VM16

SD1		VM16	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	Off-trigger
On-command	• Force: 0.5 N	• N/A	On-trigger
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 614: Proof of IF morphic equivalence between SD1 for VM16

SD1		VM16	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Trigger IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF

A.12.1.17 VM17 definition from SD1

Table 615 provides the mapping between IoX with parameterization where applicable and Table 616 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 615: Proof of IoX morphic equivalence between SD1 for VM17

SD1		VM17	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	Off-command
On-command	• Force: 0.5 N	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-off
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	Radio-on
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 616: Proof of IF morphic equivalence between SD1 for VM17

SD1		VM17	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Trigger IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF

A.12.1.18 VM18 definition from SD1

Table 617 provides the mapping between IoX with parameterization where applicable and Table 618 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 617: Proof of IoX morphic equivalence between SD1 for VM18

SD1		VM18	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	Off-command
On-command	• Force: 0.5 N	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: -5-1,000 atm • Humidity: 0-100%	Water

Table 618: Proof of IF morphic equivalence between SD1 for VM18

SD1		VM18	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF

A.12.2 Supporting results for VM defined from SD2

A.12.2.1 VM1 definition from SD2

Refer to the previous section and recall that each of the first four VM correspond to the four SD.

A.12.2.2 VM2 definition from SD2

Because the VM is a SD and the two are specified at L1, the two are said to have an identity isomorphism at L1 with respect to PSF_S1 as well as the subsets of PSF.

A.12.2.3 VM3 definition from SD2

Table 619 provides the mapping between IoX with parameterization where applicable and Table 620 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 619: Proof of IoX morphic equivalence between SD2 for VM3

SD3		VM2	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Yellow-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Yellow-light 2
Water	• Pressure: 1-5 atm	• Pressure: 1-6 atm	Water

	• Humidity: 0-100%	• Humidity: 0-100%	
No-power	• Voltage: <0.01 V	• N/A	N/A
Power	• Voltage: 3 V	• N/A	N/A

Table 620: Proof of IF morphic equivalence between SD2 for VM3

SD3		VM2	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF
Power IF	• Material: black plastic	• N/A	N/A

A.12.2.4 VM4 definition from SD2

Table 621 provides the mapping between IoX with parameterization where applicable and Table 622 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have an identity isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 621: Proof of IoX morphic equivalence between SD2 for VM4

SD2		VM4	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees	On-command 1

	• Direction: counter-clockwise	• Direction: counter-clockwise	
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Blue-light 1
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Blue-light 2
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: 1-6 atm • Humidity: 0-100%	Water
N/A	• N/A	• Voltage: <0.01 V	No-power
N/A	• N/A	• Voltage: 1.5V	Power 1
N/A	• N/A	• Voltage: 3V	Power 2

Table 622: Proof of IF morphic equivalence between SD2 for VM4

SD2		VM4	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	Water IF

N/A	• N/A	• Material: black plastic	Power IF

A.12.2.5 VM5 definition from SD2

Table 623 provides the mapping between IoX with parameterization where applicable and Table 624 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S7 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S7.

Table 623: Proof of IoX morphic equivalence between SD2 for VM5

SD2		VM5	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	N/A
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	N/A
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	• N/A	N/A
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	N/A
Blue-light 2	• Wavelength: 590 nm [yellow]	• N/A	N/A

	• Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 624: Proof of IF morphic equivalence between SD2 for VM5

SD2		VM5	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	N/A
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	N/A
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF

A.12.2.6 VM6 definition from SD2

Table 625 provides the mapping between IoX with parameterization where applicable and Table 626 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 625: Proof of IoX morphic equivalence between SD2 for VM6

SD2		VM6	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• Force: 0.5 N	Off-command
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees	• Force: 0.5 N	On-command

	• Direction: counter-clockwise		
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• N/A	N/A
N/A	• N/A	• Voltage: <0.01 V	No-power
N/A	• N/A	• Voltage: 3 V	Power
N/A	• N/A		

Table 626: Proof of IF morphic equivalence between SD2 for VM6

SD2		VM6	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A

N/A	• N/A	• Material: black plastic	Power IF

A.12.2.7 VM7 definition from SD2

Table 627 provides the mapping between IoX with parameterization where applicable and Table 628 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to remain a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 due to the lack of parameterization of the VM.

Table 627: Proof of IoX morphic equivalence between SD2 for VM7

SD2		VM7	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	0
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	1
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• N/A	0
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	1

Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• N/A	N/A

Table 628: Proof of IF morphic equivalence between SD2 for VM7

SD2		VM7	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Input IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Output IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• N/A	N/A

A.12.2.8 VM8 definition from SD2

Table 629 provides the mapping between IoX with parameterization where applicable and Table 630 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 629: Proof of IoX morphic equivalence between SD2 for VM8

SD2		VM8	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command

On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• N/A	N/A
N/A	• N/A	• Voltage: <0.01 V	No-power
N/A	• N/A	• Voltage: 5 V	Power

Table 630: Proof of IF morphic equivalence between SD2 for VM8

SD2		VM8	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm	• N/A	N/A

	• Length: 254 mm • Material: black plastic		
N/A	• N/A	• Material: black plastic	Power IF

A.12.2.9 VM9 definition from SD2

Table 631 provides the mapping between IoX with parameterization where applicable and Table 632 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 631: Proof of IoX morphic equivalence between SD2 for VM9

SD2		VM9	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light

Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 475 nm [blue] • Lumen: 200 lm	Blue-light 1
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light 2
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: 1-6 atm • Humidity: 0-100%	Water
N/A	• N/A	• Voltage: <0.01V	No-power
N/A	• N/A	• Voltage: 1V	Power 1
N/A	• N/A	• Voltage: 2V	Power 2

Table 632: Proof of IF morphic equivalence between SD2 for VM9

SD2		VM9	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
N/A	• N/A	• Material: black plastic	Power IF

A.12.2.10 VM10 definition from SD2

Table 633 provides the mapping between IoX with parameterization where applicable and Table 634 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 633: Proof of IoX morphic equivalence between SD2 for VM10

SD2		VM10	
IoX	Parameterization		IoX

Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Green to Red
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	Red to Green
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	Green to Blue
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	Blue to Green
No-light	• Lumen: <0.5 lm	• Wavelength: 650 nm [red]	Red Ink
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 510 nm [green]	Green Ink
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	• Wavelength: 475 nm [blue]	Blue Ink
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• N/A	N/A

Table 634: Proof of IF morphic equivalence between SD2 for VM10

SD2		VM10	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 5 mm • Material: black plastic	Color Change IF
Light IF	• Diameter: 57 mm	• Diameter: 2 mm	Ink IF

	• Material: clear plastic	• Material: brass	
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A

A.12.2.11 VM11 definition from SD2

Table 635 provides the mapping between IoX with parameterization where applicable and Table 636 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to remain a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 due to the lack of parameterization of the VM.

Table 635: Proof of IoX morphic equivalence between SD2 for VM11

SD2		VM11	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	Cold
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	Hot
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		

No-light	• Lumen: <0.5 lm	• N/A	No delicious smell
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	Delicious
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• N/A	N/A

Table 636: Proof of IF morphic equivalence between SD2 for VM11

SD2		VM11	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Oven IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Kitchen Air IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A

A.12.2.12 VM12 definition from SD2

Table 637 provides the mapping between IoX with parameterization where applicable and Table 638 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 637: Proof of IoX morphic equivalence between SD2 for VM12

SD2		VM12	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees	• N/A	Off-trigger

	• Direction: clockwise		
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	On-trigger
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• N/A	N/A

Table 638: Proof of IF morphic equivalence between SD2 for VM12

SD2		VM12	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Trigger IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm	• N/A	N/A

	• Length: 254 mm • Material: black plastic		

A.12.2.13 VM13 definition from SD2

Table 639 provides the mapping between IoX with parameterization where applicable and Table 640 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 639: Proof of IoX morphic equivalence between SD2 for VM13

SD2		VM13	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	Off-command
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	On-command
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-ff
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	Radio-on

Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• N/A	N/A

Table 640: Proof of IF morphic equivalence between SD2 for VM13

SD2		VM13	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Radio Display IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A

A.12.2.14 VM14 definition from SD2

Table 641 provides the mapping between IoX with parameterization where applicable and Table 642 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S7 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S7.

Table 641: Proof of IoX morphic equivalence between SD2 for VM14

SD2		VM14	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	N/A
On-command 1	• Torque: 0.5 Nm • Rotation: roll	• N/A	N/A

	• Position(s): 120 degrees • Direction: counter-clockwise		
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	• N/A	N/A
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	N/A
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	• N/A	N/A
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: -5-1000 atm • Humidity: 0-100%	Water

Table 642: Proof of IF morphic equivalence between SD2 for VM14

SD2		VM14	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	N/A
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	N/A
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF

A.12.2.15 VM15 definition from SD2

Table 643 provides the mapping between IoX with parameterization where applicable and Table 644 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S7 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S7.

Table 643: Proof of IoX morphic equivalence between SD2 for VM15

SD2		VM15	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	N/A
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	N/A
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	• N/A	N/A
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	N/A
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	• N/A	N/A
Water	• Pressure: 1-6 atm	• Pressure: 1-5 atm	Water

	• Humidity: 0-100%	• Humidity: 0-100%	

Table 644: Proof of IF morphic equivalence between SD2 for VM15

SD2		VM15	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	N/A
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	N/A
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF

A.12.2.16 VM16 definition from SD2

Table 645 provides the mapping between IoX with parameterization where applicable and Table 646 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 645: Proof of IoX morphic equivalence between SD2 for VM16

SD2		VM16	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	Off-trigger
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	On-trigger
On-command 2	• Torque: 0.5 Nm	• N/A	N/A

	• Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• N/A	N/A
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 646: Proof of IF morphic equivalence between SD2 for VM16

SD2		VM16	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Trigger IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF

A.12.2.17 VM17 definition from SD2

Table 647 provides the mapping between IoX with parameterization where applicable and Table 648 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 647: Proof of IoX morphic equivalence between SD2 for VM17

SD2		VM17	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	Off-command
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	On-command
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-ff
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	Radio-on
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water

Table 648: Proof of IF morphic equivalence between SD2 for VM17

SD2		VM17	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Trigger IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF

A.12.2.18 VM18 definition from SD2

Table 649 provides the mapping between IoX with parameterization where applicable and Table 650 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 649: Proof of IoX morphic equivalence between SD2 for VM18

SD2		VM18	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	Off-command
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	On-command
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees		

	• Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: -5-1,000 atm • Humidity: 0-100%	Water

Table 650: Proof of IF morphic equivalence between SD2 for VM18

SD2		VM18	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF

A.12.3 Supporting results for VM defined from SD3

A.12.4 VM1 definition from SD3

Refer to the previous section and recall that each of the first four VM correspond to the four SD.

A.12.2.2 VM2 definition from SD3

Refer to the previous section and recall that each of the first four VM correspond to the four SD.

A.12.2.3 VM3 definition from SD3

Because the VM is a SD and the two are specified at L2, the two are said to have an identity isomorphism at L2 and L1 with respect to PSF_S1 as well as the subsets of PSF.

A.12.2.4 VM4 definition from SD3

Table 651 provides the mapping between IoX with parameterization where applicable and Table 652 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L2 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter homomorphism at L2 and L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 651: Proof of IoX morphic equivalence between SD3 for VM4

SD3		VM4	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light

Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	Blue-light 1
		• Wavelength: 590 nm [yellow] • Lumen: 750 lm	Blue-light 2
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-6 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• Voltage: <0.01 V	No-power
Power	• Voltage: 3 V	• Voltage: 1.5V	Power 1
		• Voltage: 3V	Power 2

Table 652: Proof of IF morphic equivalence between SD3 for VM4

SD3		VM4	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• Volume: 12,800 mm^3 • Diameter: 50 mm • Length: 250 mm • Material: black plastic	N/A
Power IF	• Material: black plastic	• Material: black plastic	Power IF

A.12.2.5 VM5 definition from SD3

Table 653 provides the mapping between IoX with parameterization where applicable and Table 654 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S7 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S7.

Table 653: Proof of IoX morphic equivalence between SD3 for VM5

SD3		VM5	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	N/A

On-command	• Force: 0.5 N	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• N/A	N/A
Power	• Voltage: 3 V	• N/A	N/A

Table 654: Proof of IF morphic equivalence between SD3 for VM5

SD3		VM5	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	N/A
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	N/A
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• Volume: 14,478 mm • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF
Power IF	• Material: black plastic	• N/A	N/A

A.12.2.6 VM6 definition from SD3

Table 655 provides the mapping between IoX with parameterization where applicable and Table 656 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L2 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L2 and L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 655: Proof of IoX morphic equivalence between SD3 for VM6

SD3		VM6	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Force: 0.5 N	Off-command
On-command	• Force: 0.5 N	• Force: 0.5 N	On-command

No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A
No-power	• Voltage: <0.01 V	• Voltage: <0.01 V	No-power
Power	• Voltage: 3 V	• Voltage: 3 V	Power

Table 656: Proof of IF morphic equivalence between SD3 for VM6

SD3		VM6	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• Material: black plastic	Power IF

A.12.2.7 VM7 definition from SD3

Table 657 provides the mapping between IoX with parameterization where applicable and Table 658 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to remain a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 due to the lack of parameterization of the VM.

Table 657: Proof of IoX morphic equivalence between SD3 for VM7

SD3		VM7	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	0
On-command	• Force: 0.5 N	• N/A	1
No-light	• Lumen: <0.5 lm	• N/A	0

Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	1
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A
No-power	• Voltage: <0.01 V	• N/A	N/A
Power	• Voltage: 3 V	• N/A	N/A

Table 658: Proof of IF morphic equivalence between SD3 for VM7

SD3		VM7	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Input IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Output IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• N/A	N/A

A.12.2.8 VM8 definition from SD3

Table 659 provides the mapping between IoX with parameterization where applicable and Table 660 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L2 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L2 and L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 659: Proof of IoX morphic equivalence between SD3 for VM8

SD3		VM8	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees	Off-command

		• Direction: clockwise	
On-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A
No-power	• Voltage: <0.01 V	• Voltage: <0.01 V	No-power
Power	• Voltage: 3 V	• Voltage: 5 V	Power

Table 660: Proof of IF morphic equivalence between SD3 for VM8

SD3		VM8	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• Material: black plastic	Power IF

A.12.2.9 VM9 definition from SD3

Table 661 provides the mapping between IoX with parameterization where applicable and Table 662 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L2 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L2 and L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 661: Proof of IoX morphic equivalence between SD3 for VM9

SD3		VM9	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	On-command 1
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 475 nm [blue] • Lumen: 200 lm	Blue-light 1
		• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light 2
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-6 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• Voltage: <0.01V	No-power
Power	• Voltage: 3 V	• Voltage: 1V	Power 1
		• Voltage: 2V	Power 2

Table 662: Proof of IF morphic equivalence between SD3 for VM9

SD3		VM9	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• Material: black plastic	Power IF

A.12.2.10 VM10 definition from SD3

Table 663 provides the mapping between IoX with parameterization where applicable and Table 664 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 663: Proof of IoX morphic equivalence between SD3 for VM10

SD3		VM10	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Green to Red
On-command	• Force: 0.5 N	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	Red to Green
		• Torque: 0.5 Nm	Green to Blue

		• Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	
		• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	Blue to Green
No-light	• Lumen: <0.5 lm	• Wavelength: 650 nm [red]	Red Ink
Yellow-light	• Wavelength: 570-590 nm [yellow] • Lumen: 200-1,000 lm	• Wavelength: 510 nm [green]	Green Ink
		• Wavelength: 475 nm [blue]	Blue Ink
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A
No-power	• Voltage: <0.01 V	• N/A	N/A
Power	• Voltage: 3 V	• N/A	N/A

Table 664: Proof of IF morphic equivalence between SD3 for VM10

SD3		VM10	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 5 mm • Material: black plastic	Color Change IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 2 mm • Material: brass	Ink IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• N/A	N/A

A.12.2.11 VM11 definition from SD3

Table 665 provides the mapping between IoX with parameterization where applicable and Table 666 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to remain a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 due to the lack of parameterization of the VM.

Table 665: Proof of IoX morphic equivalence between SD3 for VM11

SD3		VM11	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	Cold
On-command	• Force: 0.5 N	• N/A	Hot
No-light	• Lumen: <0.5 lm	• N/A	No delicious smell
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	Delicious
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A
No-power	• Voltage: <0.01 V	• N/A	N/A
Power	• Voltage: 3 V	• N/A	N/A

Table 666: Proof of IF morphic equivalence between SD3 for VM11

SD3		VM11	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Oven IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Kitchen Air IF
Water IF	• Volume: 14,478 mm • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• N/A	N/A

A.12.2.12 VM12 definition from SD3

Table 667 provides the mapping between IoX with parameterization where applicable and Table 668 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 667: Proof of IoX morphic equivalence between SD3 for VM12

SD3		VM12	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	Off-trigger
On-command	• Force: 0.5 N	• N/A	On-trigger
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A
No-power	• Voltage: <0.01 V	• N/A	N/A
Power	• Voltage: 3 V	• N/A	N/A

Table 668: Proof of IF morphic equivalence between SD3 for VM12

SD3		VM12	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Trigger IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• N/A	N/A

A.12.2.13 VM13 definition from SD3

Table 669 provides the mapping between IoX with parameterization where applicable and Table 670 provides the mapping between IF with parameterization where applicable. Both

SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 669: Proof of IoX morphic equivalence between SD3 for VM13

SD3		VM13	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	Off-command
On-command	• Force: 0.5 N	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-off
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	Radio-on
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• N/A	N/A
No-power	• Voltage: <0.01 V	• N/A	N/A
Power	• Voltage: 3 V	• N/A	N/A

Table 670: Proof of IF morphic equivalence between SD3 for VM13

SD3		VM13	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Radio Display IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• N/A	N/A

A.12.2.14 VM14 definition from SD3

Table 671 provides the mapping between IoX with parameterization where applicable and Table 672 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at

L1 with respect to PSF_S7 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S7.

Table 671: Proof of IoX morphic equivalence between SD3 for VM14

SD3		VM14	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	N/A
On-command	• Force: 0.5 N	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: -5-1000 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• N/A	N/A
Power	• Voltage: 3 V	• N/A	N/A

Table 672: Proof of IF morphic equivalence between SD3 for VM14

SD3		VM14	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	N/A
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	N/A
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF
Power IF	• Material: black plastic	• N/A	N/A

A.12.2.15 VM15 definition from SD3

Table 673 provides the mapping between IoX with parameterization where applicable and Table 674 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at

L1 with respect to PSF_S7 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S7.

Table 673: Proof of IoX morphic equivalence between SD3 for VM15

SD3		VM15	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	N/A
On-command	• Force: 0.5 N	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	N/A
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• N/A	N/A
Power	• Voltage: 3 V	• N/A	N/A

Table 674: Proof of IF morphic equivalence between SD3 for VM15

SD3		VM15	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	N/A
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	N/A
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF
Power IF	• Material: black plastic	• N/A	N/A

A.12.2.16 VM16 definition from SD3

Table 675 provides the mapping between IoX with parameterization where applicable and Table 676 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 675: Proof of IoX morphic equivalence between SD3 for VM16

SD3		VM16	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	Off-trigger
On-command	• Force: 0.5 N	• N/A	On-trigger
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• N/A	N/A
Power	• Voltage: 3 V	• N/A	N/A

Table 676: Proof of IF morphic equivalence between SD3 for VM16

SD3		VM16	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Trigger IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF
Power IF	• Material: black plastic	• N/A	N/A

A.12.2.17 VM17 definition from SD3

Table 677 provides the mapping between IoX with parameterization where applicable and Table 678 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 677: Proof of IoX morphic equivalence between SD3 for VM17

SD3		VM17	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	Off-command
On-command	• Force: 0.5 N	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-off
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• N/A	Radio-on
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• N/A	N/A
Power	• Voltage: 3 V	• N/A	N/A

Table 678: Proof of IF morphic equivalence between SD3 for VM17

SD3		VM17	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Trigger IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF
Power IF	• Material: black plastic	• N/A	N/A

A.12.2.18 VM18 definition from SD3

Table 679 provides the mapping between IoX with parameterization where applicable and Table 680 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 679: Proof of IoX morphic equivalence between SD3 for VM18

SD3		VM18	
IoX	Parameterization		IoX
Off-command	• Force: 0.5 N	• N/A	Off-command
On-command	• Force: 0.5 N	• N/A	On-command
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Yellow-light	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Water	• Pressure: 1-5 atm • Humidity: 0-100%	• Pressure: -5-1,000 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• N/A	N/A
Power	• Voltage: 3 V	• N/A	N/A

Table 680: Proof of IF morphic equivalence between SD3 for VM18

SD3		VM18	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF
Power IF	• Material: black plastic	• N/A	N/A

A.12.4 Supporting results for VM defined from SD4

A.12.4.1 VM1 definition from SD4

Refer to the previous section and recall that each of the first four VM correspond to the four SD.

A.12.4.2 VM2 definition from SD4

Refer to the previous section and recall that each of the first four VM correspond to the four SD.

A.12.4.3 VM3 definition from SD4

Refer to the previous section and recall that each of the first four VM correspond to the four SD.

A.12.4..4 VM4 definition from SD4

Because the VM is a SD and the two are specified at L2, the two are said to have an identity isomorphism at L2 and L1 with respect to PSF_S1 as well as the subsets of PSF.

A.12.4.5 VM5 definition from SD4

Table 681 provides the mapping between IoX with parameterization where applicable and Table 682 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S7 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S7.

Table 681: Proof of IoX morphic equivalence between SD4 for VM5

SD4		VM5	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	N/A
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	N/A
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	• N/A	N/A
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A

Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	N/A
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	• N/A	N/A
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• N/A	N/A
Power 1	• Voltage: 1.5V	• N/A	N/A
Power 2	• Voltage: 3V	• N/A	N/A

Table 682: Proof of IF morphic equivalence between SD4 for VM5

SD4		VM5	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	N/A
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	N/A
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• Volume: 14,478 mm • Diameter: 57 mm • Length: 254 mm • Material: black plastic	Water IF
Power IF	• Material: black plastic	• N/A	N/A

A.12.4.6 VM6 definition from SD4

Table 683 provides the mapping between IoX with parameterization where applicable and Table 684 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L2 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L2 and L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 683: Proof of IoX morphic equivalence between SD4 for VM6

SD4		VM6	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• Force: 0.5 N	Off-command
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• Force: 0.5 N	On-command
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• N/A	N/A
No-power	• Voltage: <0.01 V	• Voltage: <0.01 V	No-power
Power 1	• Voltage: 1.5V	• Voltage: 3 V	Power
Power 2	• Voltage: 3V		

Table 684: Proof of IF morphic equivalence between SD4 for VM6

SD4		VM6	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• Material: black plastic	Power IF

A.12.4.7 VM7 definition from SD4

Table 685 provides the mapping between IoX with parameterization where applicable and Table 686 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to remain a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 due to the lack of parameterization of the VM.

Table 685: Proof of IoX morphic equivalence between SD4 for VM7

SD4		VM7	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	0
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	1
On-command 2	• Torque: 0.5 Nm • Rotation: roll		

	• Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• N/A	0
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	1
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• N/A	N/A
No-power	• Voltage: <0.01 V	• N/A	N/A
Power 1	• Voltage: 1.5V	• N/A	N/A
Power 2	• Voltage: 3V	• N/A	N/A

Table 686: Proof of IF morphic equivalence between SD4 for VM7

SD4		VM7	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Input IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Output IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• N/A	N/A

A.12.4.8 VM8 definition from SD4

Table 687 provides the mapping between IoX with parameterization where applicable and Table 688 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L2 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L2 and L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 687: Proof of IoX morphic equivalence between SD4 for VM8

<table>
<tr><th colspan="2">SD4</th><th colspan="2">VM8</th></tr>
<tr><th>IoX</th><th colspan="2">Parameterization</th><th>IoX</th></tr>
<tr><td>Off-command</td><td>• Torque: 0.5 Nm
• Rotation: roll
• Position: 0 degrees
• Direction: clockwise</td><td>• Torque: 0.5 Nm
• Rotation: roll
• Position: 0 degrees
• Direction: clockwise</td><td>Off-command</td></tr>
<tr><td>On-command 1</td><td>• Torque: 0.5 Nm
• Rotation: roll
• Position(s): 120 degrees
• Direction: counter-clockwise</td><td rowspan="3">• Torque: 0.5 Nm
• Rotation: roll
• Position(s): 120 degrees
• Direction: counter-clockwise</td><td rowspan="3">On-command</td></tr>
<tr><td>On-command 2</td><td>• Torque: 0.5 Nm
• Rotation: roll
• Position(s): 240 degrees
• Direction: counter-clockwise</td></tr>
<tr><td>On-command 3</td><td>• Torque: 0.5 Nm
• Rotation: roll
• Position(s): 120 degrees
• Direction: clockwise</td></tr>
<tr><td>No-light</td><td>• Lumen: <0.5 lm</td><td>• Lumen: <0.5 lm</td><td>No-light</td></tr>
<tr><td>Blue-light 1</td><td>• Wavelength: 590 nm [yellow]
• Lumen: 250 lm</td><td rowspan="2">• Wavelength: 475 nm [blue]
• Lumen: 400 lm</td><td rowspan="2">Blue-light</td></tr>
<tr><td>Blue-light 2</td><td>• Wavelength: 590 nm [yellow]
• Lumen: 750 lm</td></tr>
<tr><td>Water</td><td>• Pressure: 1-6 atm</td><td>• N/A</td><td>N/A</td></tr>
</table>

	• Humidity: 0-100%		
No-power	• Voltage: <0.01 V	• Voltage: <0.01 V	No-power
Power 1	• Voltage: 1.5V	• Voltage: 5 V	Power
Power 2	• Voltage: 3V		

Table 688: Proof of IF morphic equivalence between SD4 for VM8

SD4		VM8	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 15 mm • Material: black rubber	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 57 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• Material: black plastic	Power IF

A.12.4.9 VM9 definition from SD4

Table 689 provides the mapping between IoX with parameterization where applicable and Table 690 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L2 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L2 and L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 689: Proof of IoX morphic equivalence between SD4 for VM9

SD4		VM9	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Off-command
On-command 1	• Torque: 0.5 Nm	• Torque: 0.5 Nm	On-command 1

	• Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	On-command 2
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	On-command 3
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 475 nm [blue] • Lumen: 200 lm	Blue-light 1
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	• Wavelength: 475 nm [blue] • Lumen: 400 lm	Blue-light 2
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: 1-6 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• Voltage: <0.01V	No-power
Power 1	• Voltage: 1.5V	• Voltage: 1V	Power 1
Power 2	• Voltage: 3V	• Voltage: 2V	Power 2

Table 690: Proof of IF morphic equivalence between SD4 for VM9

SD4		VM9	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 50 mm • Material: black plastic	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 45 mm • Material: clear plastic	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm	• N/A	N/A

	• Length: 254 mm • Material: black plastic		
Power IF	• Material: black plastic	• Material: black plastic	Power IF

A.12.4.10 VM10 definition from SD4

Table 691 provides the mapping between IoX with parameterization where applicable and Table 692 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 691: Proof of IoX morphic equivalence between SD4 for VM10

SD4		VM10	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	Green to Red
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	Red to Green
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	Green to Blue
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	Blue to Green
No-light	• Lumen: <0.5 lm	• Wavelength: 650 nm [red]	Red Ink

Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 510 nm [green]	Green Ink
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	• Wavelength: 475 nm [blue]	Blue Ink
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• N/A	N/A
No-power	• Voltage: <0.01 V	• N/A	N/A
Power 1	• Voltage: 1.5V	• N/A	N/A
Power 2	• Voltage: 3V	• N/A	N/A

Table 692: Proof of IF morphic equivalence between SD4 for VM10

SD4		VM10	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• Diameter: 5 mm • Material: black plastic	Color Change IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• Diameter: 2 mm • Material: brass	Ink IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• N/A	N/A

A.12.4.11 VM11 definition from SD4

Table 693 provides the mapping between IoX with parameterization where applicable and Table 694 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to remain a homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 due to the lack of parameterization of the VM.

Table 693: Proof of IoX morphic equivalence between SD4 for VM11

SD4		VM11	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	Cold
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	Hot
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• N/A	No delicious smell
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	Delicious
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• N/A	N/A
No-power	• Voltage: <0.01 V	• N/A	N/A
Power 1	• Voltage: 1.5V	• N/A	N/A
Power 2	• Voltage: 3V	• N/A	N/A

Table 694: Proof of IF morphic equivalence between SD4 for VM11

SD4		VM11	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Oven IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Kitchen Air IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• N/A	N/A

A.12.4.12 VM12 definition from SD4

Table 695 provides the mapping between IoX with parameterization where applicable and Table 696 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 695: Proof of IoX morphic equivalence between SD4 for VM12

SD4		VM12	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	Off-trigger
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	On-trigger
On-command 2	• Torque: 0.5 Nm • Rotation: roll		

	• Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• N/A	N/A
No-power	• Voltage: <0.01 V	• N/A	N/A
Power 1	• Voltage: 1.5V	• N/A	N/A
Power 2	• Voltage: 3V	• N/A	N/A

Table 696: Proof of IF morphic equivalence between SD4 for VM12

SD4		VM12	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Trigger IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• N/A	N/A

A.12.4.13 VM13 definition from SD4

Table 697 provides the mapping between IoX with parameterization where applicable and Table 698 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S2, PSF_S3, and PSF_S4 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S2, PSF_S3, and PSF_S4.

Table 697: Proof of IoX morphic equivalence between SD4 for VM13

SD4		VM13	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	Off-command
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	On-command
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-ff
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	Radio-on
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm	• N/A	N/A

	• Humidity: 0-100%		
No-power	• Voltage: <0.01 V	• N/A	N/A
Power 1	• Voltage: 1.5V	• N/A	N/A
Power 2	• Voltage: 3V	• N/A	N/A

Table 698: Proof of IF morphic equivalence between SD4 for VM13

SD4		VM13	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Radio Display IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	N/A
Power IF	• Material: black plastic	• N/A	N/A

A.12.4.14 VM14 definition from SD4

Table 699 provides the mapping between IoX with parameterization where applicable and Table 700 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S7 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S7.

Table 699: Proof of IoX morphic equivalence between SD4 for VM14

SD4		VM14	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	N/A
On-command 1	• Torque: 0.5 Nm • Rotation: roll	• N/A	N/A

	• Position(s): 120 degrees • Direction: counter-clockwise		
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	• N/A	N/A
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	N/A
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	• N/A	N/A
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: -5-1000 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• N/A	N/A
Power 1	• Voltage: 1.5V	• N/A	N/A
Power 2	• Voltage: 3V	• N/A	N/A

Table 700: Proof of IF morphic equivalence between SD4 for VM14

SD4		VM14	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	N/A
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	N/A
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm	• N/A	Water IF

	• Length: 254 mm • Material: black plastic		
Power IF	• Material: black plastic	• N/A	N/A

A.12.4.15 VM15 definition from SD4

Table 701 provides the mapping between IoX with parameterization where applicable and Table 702 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be homomorphic at L1 with respect to PSF_S7 only. From the results in this section, the two SM may be said to have a parameter homomorphism at L1 with respect to PSF_S7.

Table 701: Proof of IoX morphic equivalence between SD4 for VM15

SD4		VM15	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	N/A
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	N/A
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	• N/A	N/A
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• N/A	N/A
No-light	• Lumen: <0.5 lm	• N/A	N/A
Blue-light 1	• Wavelength: 590 nm [yellow]	• N/A	N/A

	• Lumen: 250 lm		
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm	• N/A	N/A
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• N/A	N/A
Power 1	• Voltage: 1.5V	• N/A	N/A
Power 2	• Voltage: 3V	• N/A	N/A

Table 702: Proof of IF morphic equivalence between SD4 for VM15

SD4		VM15	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	N/A
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	N/A
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF
Power IF	• Material: black plastic	• N/A	N/A

A.12.4.16 VM16 definition from SD4

Table 703 provides the mapping between IoX with parameterization where applicable and Table 704 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 703: Proof of IoX morphic equivalence between SD4 for VM16

SD4		VM16	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll	• N/A	Off-trigger

	• Position: 0 degrees • Direction: clockwise		
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	On-trigger
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise	• N/A	N/A
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise	• N/A	N/A
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 590 nm [yellow] • Lumen: 325 lm	Firefly light
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• N/A	N/A
Power 1	• Voltage: 1.5V	• N/A	N/A
Power 2	• Voltage: 3V	• N/A	N/A

Table 704: Proof of IF morphic equivalence between SD4 for VM16

SD4		VM16	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Trigger IF
Light IF	• Diameter: 57 mm	• N/A	Light IF

	• Material: clear plastic		
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF
Power IF	• Material: black plastic	• N/A	N/A

A.12.4.17 VM17 definition from SD4

Table 705 provides the mapping between IoX with parameterization where applicable and Table 706 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 705: Proof of IoX morphic equivalence between SD4 for VM17

SD4		VM17	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	Off-command
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	On-command
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees		

	• Direction: clockwise		
No-light	• Lumen: <0.5 lm	• Lumen: <0.5	Radio-ff
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• N/A	Radio-on
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: 1-5 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• N/A	N/A
Power 1	• Voltage: 1.5V	• N/A	N/A
Power 2	• Voltage: 3V	• N/A	N/A

Table 706: Proof of IF morphic equivalence between SD4 for VM17

SD4		VM17	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	Trigger IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF
Power IF	• Material: black plastic	• N/A	N/A

A.12.4.18 VM18 definition from SD4

Table 707 provides the mapping between IoX with parameterization where applicable and Table 708 provides the mapping between IF with parameterization where applicable. Both SM that the VM are parameterizations of were previously proven to be isomorphic at L1 with respect to PSF_S1. From the results in this section, the two SM may be said to have a parameter isomorphism at L1 with respect to PSF_S1 as well as with the PSF subsets.

Table 707: Proof of IoX morphic equivalence between SD4 for VM18

SD4		VM18	
IoX	Parameterization		IoX
Off-command	• Torque: 0.5 Nm • Rotation: roll • Position: 0 degrees • Direction: clockwise	• N/A	Off-command
On-command 1	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: counter-clockwise	• N/A	On-command
On-command 2	• Torque: 0.5 Nm • Rotation: roll • Position(s): 240 degrees • Direction: counter-clockwise		
On-command 3	• Torque: 0.5 Nm • Rotation: roll • Position(s): 120 degrees • Direction: clockwise		
No-light	• Lumen: <0.5 lm	• Lumen: <0.5 lm	No-light
Blue-light 1	• Wavelength: 590 nm [yellow] • Lumen: 250 lm	• Wavelength: 580 nm [yellow] • Lumen: 500 lm	Yellow-light
Blue-light 2	• Wavelength: 590 nm [yellow] • Lumen: 750 lm		
Water	• Pressure: 1-6 atm • Humidity: 0-100%	• Pressure: -5-1,000 atm • Humidity: 0-100%	Water
No-power	• Voltage: <0.01 V	• N/A	N/A
Power 1	• Voltage: 1.5V	• N/A	N/A
Power 2	• Voltage: 3V	• N/A	N/A

Table 708: Proof of IF morphic equivalence between SD4 for VM18

SD4		VM18	
IF	Parameterization		IF
On/off IF	• Diameter: 15 mm • Material: black rubber	• N/A	On/off IF
Light IF	• Diameter: 57 mm • Material: clear plastic	• N/A	Light IF
Water IF	• Volume: 14,478 mm^3 • Diameter: 57 mm • Length: 254 mm • Material: black plastic	• N/A	Water IF
Power IF	• Material: black plastic	• N/A	N/A