Early alignment of design requirements with stakeholder needs

V Agouridas[1]*, H Winand[2], A McKay[1], and A de Pennington[1]
[1] School of Mechanical Engineering, University of Leeds, Leeds, UK
[2] Corporate Venturing, Rolls-Royce plc, Derby, UK

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Abstract: Informality of design requirements is a problem, especially in distributed design teams, because it impacts upon the ability of a team to communicate. Since design requirements drive the design process, their miscommunication results in serious problems; for example, new products that do not align with the needs of the range of stakeholders to whom they are targeted. This, in turn, has a detrimental impact on traditional business performance indicators, such as market share, volume of sales, and profit. The research reported in this paper explored the applicability of requirements engineering and management techniques, traditionally used in the development of software-intensive systems, to the development of electromechanical consumer products. The motivational rationale traceability matrix (MoRal$_{TM}$) is introduced as a means to support the initial analysis of stakeholder needs and attributes, and the derivation of corresponding design requirements. The applicability of MoRal$_{TM}$ is demonstrated through application to a power solution case study. In this instance, the MoRal$_{TM}$ proved to be a powerful means of supporting the derivation of design requirements that are aligned with customer and other stakeholder needs, and are traceable to stakeholder intents.

Keywords: stakeholder requirements, customer needs, design requirements, requirements engineering and management, engineering design, product design, motivational rationale

1 INTRODUCTION

A successful consumer product can be considered as a system that satisfies consumer and other stakeholder needs [**1**]. To remain competitive, manufacturing enterprises increasingly need to be able to deliver such products to the marketplace with appropriate functionality and quality, differentiated from the competition and available at an appropriate price [**2–5**]. To meet this challenge, and to meet the pressures of increasing globalization, enterprises have become more open and collaborate with other enterprises [**6**]. This has led to the term 'extended enterprise' [**7–9**].

A result of the extended enterprise is that many people from diverse areas of expertise and who are often geographically dispersed are required to work together to develop products [**10**, **11**]. As a result, there is an increased need for effective communication throughout the design process. The early phases of the design process, as described by Ulrich and Eppinger [**12**], Cagan and Vogel [**13**], and Pahl and Beitz [**14**], are critical. As Fig. 1 shows, decisions made early in the design process have a profound impact on a project's committed costs. In addition, design changes made during the later phases can be very expensive. One way to avoid or reduce such changes is the enhancement of the early decision making.

One aspect of the early phases of the design process that requires effective communication is the derivation of design requirements for totally new products. The use of requirements engineering and management techniques is important because competitive pressures force engineering enterprises to deliver complex technology solutions – in very competitive markets. This situation is further exacerbated by the fact that distribution of product

Corresponding author: School of Mechanical Engineering, University of Leeds, Woodhouse Lane, Leeds, West Yorkshire LS2 9JT, UK. email: V.Agouridas@leeds.ac.uk

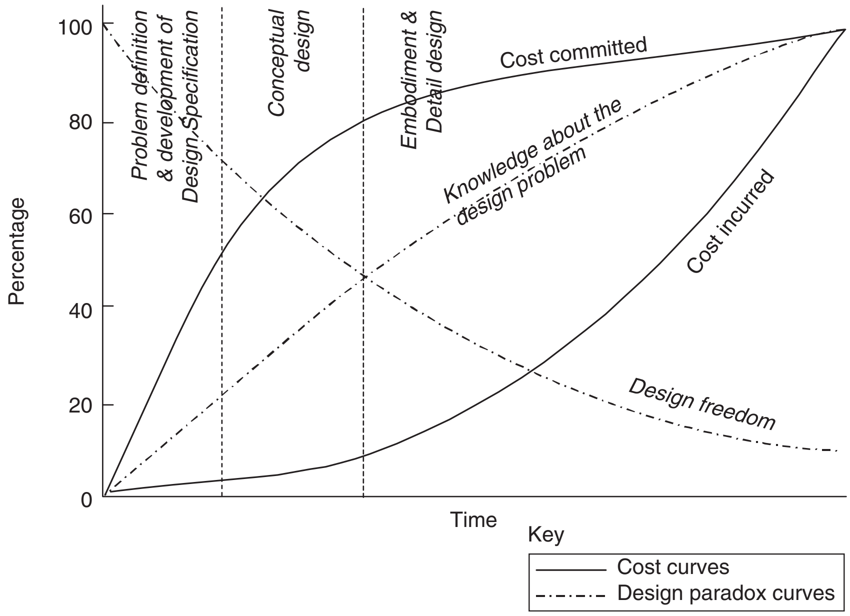

Fig. 1 Superimposed cost and design paradox curves (adapted from Agouridas *et al.* [**15**])

development tasks across extended enterprises is becoming more common.

The majority of requirements engineering literature deals with the development of software-intensive systems. Literature associated with the early phases of the design process addresses the formal documentation of design goals. A number of goal-driven techniques have been presented [**16**]. However, they do not support the derivation of intent-driven goals. In other words, goals, and their corresponding solutions, are neither systematically derived from stakeholder needs, nor demonstrably traceable to stakeholder intents. Instead, goals are taken for granted and formalized through specification languages that allow development of low-level software design requirements. In the development of totally new consumer products, the applicability and effectiveness of such tools requires that the motivational triggers of customers and other significant stakeholders are sufficiently defined (i.e. not taken for granted) and demonstrably aligned with the developed solutions [**1**]. The term 'motivational triggers' refers to the expectations that stakeholders have for satisfying both articulated or unarticulated (latent) needs, and/or established or perceived needs.

Recent research in requirements engineering and management originating from the electromechanical domain reported a number of issues associated with the identification and application of design requirements. For example, Chakrabarti *et al.* [**17**] highlighted the significance of identifying and clarifying design requirements to the quality of the outcome of the design process; they reported that the number of design requirements used is typically less than but proportional to the number of design requirements identified. This implies that many design requirements are not satisfied and indicates the lack of comprehensive requirements analysis activities. Hence, there is a need for design support tools that allow for the systematic derivation of design requirements. Such tools support the derivation of design requirements that are fully aligned with customer and other stakeholder needs. Consequently, this avoids inconsistencies and discrepancies of *ad hoc* processes that eventually lead to the production of over-specified lists of design requirements.

Eckert *et al.* [**18**] reported research on change management in complex engineering domains which concluded that the role of requirements engineering and management during the early phases of the design process is critical. Their study dealt with design changes occurring in the contract-to-deliver phase of the design process and the problems and activities that originate from such changes. The changes under consideration were associated with selected design parameters and the satisfaction of design requirements, and they were referred to as 'emergent changes'. However, problems and activities that originate from changes associated with customer requirements and their consequent effect to the derivation of design requirements were not studied in depth. It has to be noted, though, that the authors acknowledged such changes as being of equal importance to emergent ones and referred to them as 'initiated changes'. One of the aims of the research reported in this paper has been to support change management through improved traceability of the early phases of the design process.

Many requirements traceability approaches support so-called ‘post-traceability’ [**19**, **20**]; that is, focusing on the trace of hierarchical decompositions from high-level to low-level design (technical) requirements [**21**]. This requires the provision of design rationale structures [**22**, **23**]. Such structures make design reasoning explicit for the purposes of guiding decision making, keeping track of conceptual and detailed designs, and accumulating knowledge about potential solutions. Ultimately, post-traceability approaches can be used to ensure that all high-level design requirements are properly flowed down to all levels with no design requirement lost and none added. Other traceability approaches support so-called ‘pretraceability’ [**24**, **25**]. That is, focusing on the trace of the derivation of design requirements based on stakeholder requirements. An effective pretraceability approach supports a product development team to augment its confidence that the derived design requirements fully capture all significant intents of stakeholders and are explicitly traceable to those intents. An intentional structure[1] is therefore a critical element of any pretraceability approach. However, the high degree of informality that typifies the early phases of product development is a significant barrier to the development and use of an integrated methodology for requirements engineering and the management of electromechanical products [**27**, **28**]. This can prove costly especially when launching totally new products. The goal of the research reported in this paper was to establish an approach for the systematic derivation of design requirements from stakeholder needs.

Haque and Moore [**29**] commented that if new product introduction processes are to benefit from the principles of lean thinking [**30**] in a way similar to that of manufacturing processes, then metrics need to be identified that are conducive to lean thinking. This research identified metrics that relate to the derivation of design requirements from stakeholder needs in the context of improving the efficiency and effectiveness of customer-centric new product introduction processes.

1.1 Structure of the paper

The research methodology is outlined in section 2. Section 3 provides a review of literature on the derivation of design requirements with a focus on literature associated with the characterization of stakeholder requirements. Section 4 gives an overview, through an IDEFØ[2] [**31**] activity model, of the main processes involved in the derivation of design requirements from stakeholder needs. This is followed by an introduction to the motivational rationale traceability matrix (MoRal$_{TM}$) as a means of supporting the systematic definition, analysis, and traceability of interdependencies between stakeholder requirements, and a description of the key characteristics of MoRal$_{TM}$. Section 5 describes an application and evaluation of MoRal$_{TM}$ through a case study drawn from the power sector. Section 6 presents the conclusions drawn and gives directions for future research.

2 RESEARCH METHODOLOGY

The research methodology is the outcome of a consolidation of the positivistic and naturalistic paradigms [**32**, **33**]. This allowed the research to take into account both the technical and social aspects of design [**34–36**] achieved through a consolidation of the principles and process elements of hypothesis-testing, action research, and case study research methodologies.

2.1 Key characteristics of the research methodology

Action research constitutes the kernel of the research methodology, enhanced with contributions from hypothesis-testing and case-study-based methodologies. This is because the linkage of design research to design practice has been identified as a significant challenge in design theory and methodology research [**37–39**]. Figure 2 shows the three key elements of the research methodology:

(a) the research framework (e.g. MoRal$_{TM}$ and the literature associated with it);
(b) the real-world problem situation (e.g. the derivation of design requirements for a new product);
(c) the structured experience (e.g. the systematic acquisition and documentation of data through semi-structured interviews).

The above elements are linked through a number of relationships that are also depicted in Fig. 2.

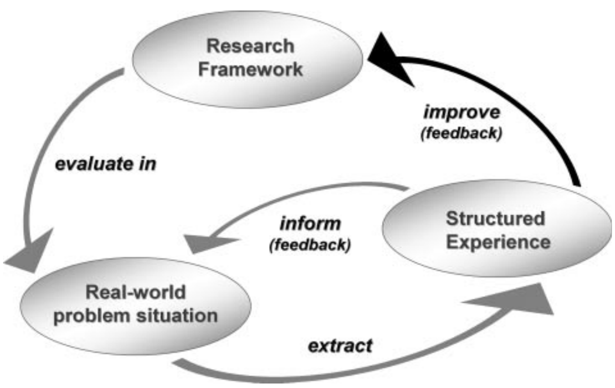

Fig. 2 Abstract depiction of the research methodology process cycle

evaluate in the application of the research framework to a real-world problem situation; this sets the context for evaluation through elicitation and documentation of evidence
extract the elicitation and documentation of evidence from the real-world problem situation
inform the dissemination of new learning to the real-world problem situation
improve the refinement of the research framework

The methodology sets the basis for the completion of a series of research process cycles that led to the research results reported in this paper.

The remainder of the paper is structured around the key characteristics of the research methodology. Hence, section 3 reviews literature that constituted part of the research framework. Section 4 outlines the developed IDEFØ activity model and introduces $\mathrm{MoRal}_{\mathrm{TM}}$; both of these relate to the research framework. Section 5 describes an application/evaluation of $\mathrm{MoRal}_{\mathrm{TM}}$ through a case study that deals with a real-world problem situation and links it to the research methodology. It also provides (section 5.2) a discussion on the application of $\mathrm{MoRal}_{\mathrm{TM}}$ that relates to the structured experience and inform elements of the methodology outlined in Fig. 2. Section 6, which relates to the improve element of the methodology, presents the conclusions drawn from the reported research activity and gives directions for future research.

3 THE DERIVATION OF DESIGN REQUIREMENTS

Life-cycle engineering has emerged as an approach aiming to maximize the contribution of a product to society while minimizing the economic, social, and environmental costs to its stakeholders (e.g. user, manufacturer, and the various regulatory agencies) [**40**, **41**]. To achieve this, life-cycle engineering aims to address a number of life-cycle issues during the early stages of design [**40**, **42**, **43**]. For example, according to Ishii [**43**], life-cycle engineering requires designers to estimate life-cycle costs and attribute them to design and manufacturing decisions. With regard to design decisions, the principles of concurrent engineering have played a significant role in the manner in which such decisions are made. Benefits with respect to reduction of life-cycle costs from the implementation of concurrent engineering principles stem from the simultaneous consideration of life-cycle issues from the early phases of the product development process. That is, life-cycle engineering goes beyond the design of the product itself. It is simultaneously concerned with the life of the manufacturing process and of the product service system. Figure 3 depicts the three life cycles that set the basis for concurrent engineering [**44**].

Shifting from the traditional sequential manner of product development requires the use of structured approaches, early in the development process, for gathering and managing data related to, for example, customers, manufacturing operations, maintenance or logistics. A prevalent structured approach for this has been the technique of quality function deployment (QFD) [**45**, **46**]. However, QFD has been criticized for its relative ineffectiveness at translating customer and other stakeholder needs into engineering characteristics. This is particularly true for totally new products [**47–50**].

Suh [**21**] represented the design process by way of a loop. Figure 4 shows that the design process commences with the recognition of a societal need

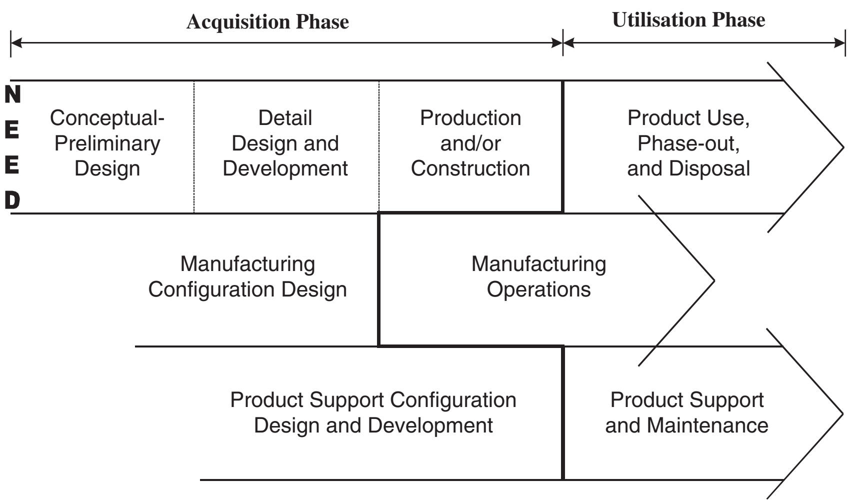

Fig. 3 Product, manufacturing, and support life cycles (adapted from Blanchard and Fabrycky [**44**])

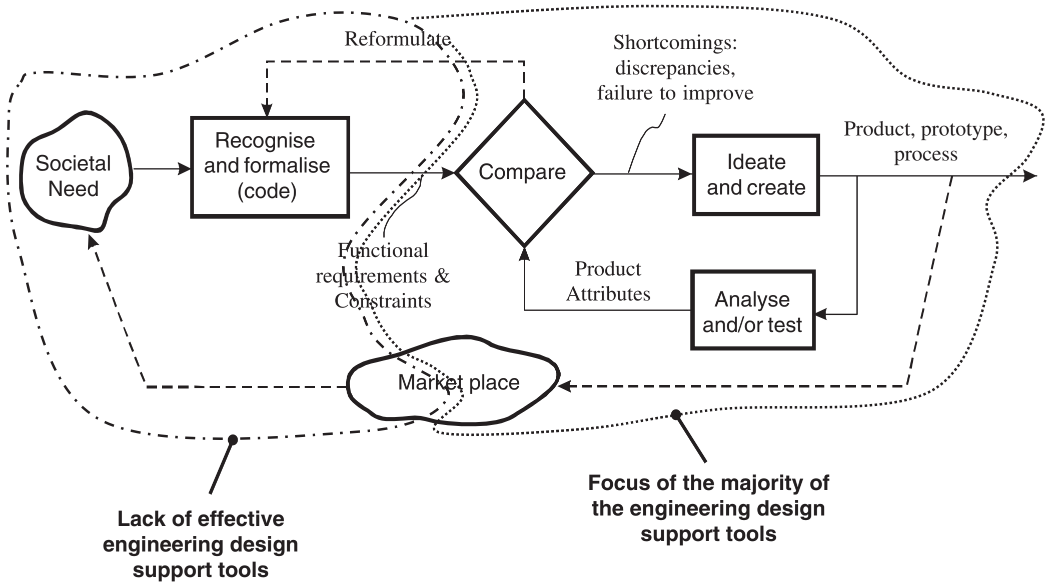

Fig. 4 The design process loop (adapted from Suh [**21**])

followed by its formalization in a set of functional requirements and constraints that define the design problem and set the design goals. Activities of synthesis and analysis follow. The majority of design methodologies deal with the synthesis, analysis, comparison, and evaluation of solutions. Systematic methods for the transformation of a given function structure to corresponding design parameters [**21**], related geometry [**51**], and shape [**52**], have been established. For example, Suh [**21**, **28**] has put forward a systematic approach for the evolution of functional requirements by way of decomposition through the principles of axiomatic design theory.

Figures 3 and 4 indicate that no matter how the design process is represented, a prime activity is the identification and capture of the needs of the stakeholders[3] and their translation into design requirements. For example, as shown in Fig. 4, the definition of functional requirements and constraints is critical to the entire design process since these represent the design goals against which design concepts are compared and evaluated. Systematic methods that deal with the recognize and formalize phase (see Fig. 4) are lacking. For this reason *ad hoc* practices are deployed instead [**28, 44**].

The key role of design requirements specification has been highlighted by Andersson [**53**] who represented the iteration between synthesis and analysis on different levels, as shown in Fig. 5.

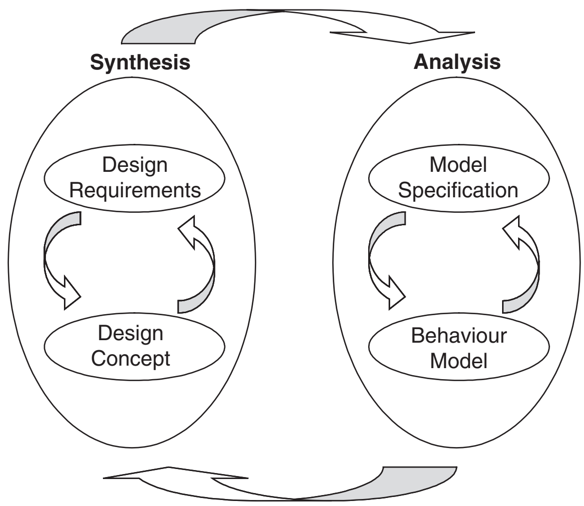

Fig. 5 Iteration loops on different levels (adapted from Andersson [**53**])

Figure 5 shows that an outer iteration loop between synthesis and analysis involves inner iterations between design requirements and a design concept, and between a model specification and a behaviour model respectively. However, it fails to show that the derivation of design requirements is a result not only of an interplay between design concepts but also between stakeholder requirements. Key to managing such linkages is the characterization of the stakeholder requirements. Section 3.1 reviews the literature associated with the characterization of such requirements and the derivation of corresponding design requirements.

3.1 The characterization of stakeholder requirements

The characterization of stakeholder requirements and the derivation of corresponding design requirements can be seen as a process that is informed from diverse research areas. The difficulty of executing such processes has been recognized in the literature [**28**, **44**, **54**]; for example, Suh [**28**] acknowledges that the mapping of customer needs to functional

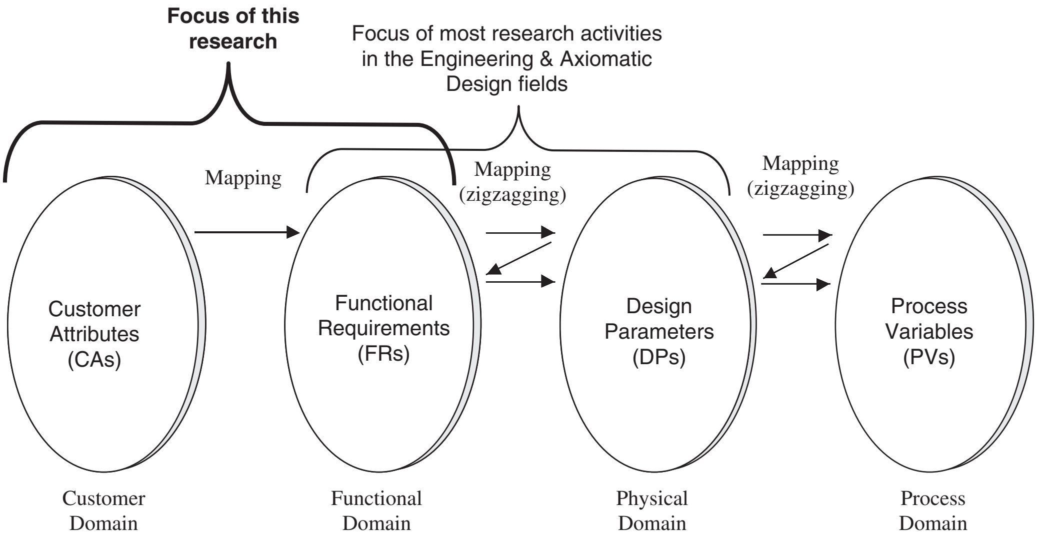

Fig. 6 Depiction of the focus of the research

requirements is of major importance in the design process. He notes that even when customer needs are established, their mapping to functional requirements is not a trivial task and requires a significant amount of time for discussion and analysis.

Figure 6 depicts the focus of the research reported in this paper with respect to other research efforts in the field of engineering design using the design domains, as represented in the axiomatic design theory [**21**, **28**, **55**].

Significant interdisciplinary research work can be found in literature associated with the early stages of product and engineering design (shown in Fig. 6 as the customer and functional domains, and the mapping between them) (e.g. **56–59**). For the purposes of this paper, the topics of interest have been grouped into the following four categories.

1. Requirements elicitation techniques.
2. Requirements or design rationale methods.
3. Approaches for linking customer requirements to design requirements (here, referred to as requirements connectivity).
4. Approaches to requirements management.

3.1.1 Requirements elicitation techniques

Research in this category can be grouped into three sub-categories: acquisition of customer requirements (also referred to as capture or identification), analysis of customer requirements, and assessment of customer requirements.

Acquisition of customer requirements – Bruce, Wooton and Cooper [**60**] provide a framework for a requirements capture process. However, this framework is limited to a set of necessary activities, by way of guidelines, for accomplishing effective requirements capture. An explicit method for capturing requirements is not provided. Yan, Chen, and Khoo [**61**] argue that they can elicit customer requirements through an integrated approach based on a sorting technique of single-criterion and fuzzy evaluation. However, sorting techniques are only effective for identifying objective customer requirements based on the preferences of the customers. That is, they are appropriate for ensuring the definition of product attributes, but they are not suitable for identifying the underlying needs (apparent or latent) of customers. Morris, Stauffer, and Khadilkar [**56**] use a customer-focused design taxonomy for identifying customer requirements from a diversity of sources in a given customer context. However, the effectiveness of this kind of taxonomy is biased by the subjective nature of the data gathered from the customers. Again, Morris *et al.* [**56**] do not address the identification of customer needs. Maruca [**62**] identifies a need for a systematic way for delineating customer needs in more depth[4] than such taxonomies allow. Furthermore, the relationships between the different types of customer data need to be explicitly articulated.

Analysis of customer requirements – Fung, Popplewell, and Xie [**64**] propose an approach for analysing customer requirements through combining the principles of quality function deployment (QFD), analytic hierarchy process, and fuzzy set theory. However, the analysis focuses only on determining technical design targets from specific customer requirements; it is assumed that the analysed customer requirements represent the underlying needs and attributes of the customers. Eodice, Leifer, and Fruchter [**65**] propose the analysis of requirements through the method of problem-reduction. Although they distinguish between needs and requirements, they imply that needs relate to customer requirements and requirements to design requirements; thus, they equate customer needs to customer requirements. Further, they associate design requirements with specific solutions, thus failing to acknowledge a key distinction between different kinds of design requirement; namely, between design requirements that are derived from stakeholder needs (i.e. solution-independent design requirements) and design requirements that are derived from, and coupled with, design parameters (i.e. solution-dependent design requirements).

Assessment of customer requirements – The importance of careful customer needs assessment in new product development has been stressed by many researchers [**58**, **59**, **66**]. A considerable number of research efforts have focused on the application of the technique of conjoint analysis for assessing customer requirements during product development. These efforts [**61**, **57**] primarily aim to provide an understanding of product preferences and trade-offs through assessment of customer preferences from a number of product attributes. However, such efforts only address the assessment of established customer needs. As emphasized by Karkkainen and Elfvengren [**59**], the assessment of new customer needs (hidden and future) plays an important role in the successful development of new products. Findings from their research indicated that 60 per cent of enterprises did not use any systematic method for the assessment of new customer needs. The research reported in this paper offers a systematic approach to the analysis of customer and other stakeholder requirements by providing qualitative and quantitative analysis of the interdependencies between stakeholder requirements.

3.1.2 Requirements or design rationale methods

Ullman [**67**] reported that a way forward for computer-aided design (CAD) systems is the integration of the functional requirements developed with QFD-type methods and the constraints on function and geometry that drive the development of components. He further commented that as the design process evolves from conceptual to detail design, there is a shift on the source of constraints imposed on the design: from constraints imposed outside the control of the designer to constraints imposed based on previous design decisions. Consequently, Ullman highlighted a need to support reasoning behind design decisions. The use of design rationale systems could be one way forward. For example, Reich [**68**] adapted QFD to improve its capability with respect to capturing design rationale, and Stahovich and Raghavan [**69**] offered an approach for computing causal explanations of the purposes of the geometric features on the parts of a device. Brazier, Langen, and Treur [**70**] developed a generic task model that specifies the role of design history and design rationale within the design process. The model distinguishes between different types of design rationale based on the functional role they play in the design process. These include information, for example, about options considered for the design decisions and criteria upon which design decisions were made. Regli and others [**71**] reported a survey on design rationale systems and concluded that, although a number of prototype systems have been developed, the majority of them are still in the laboratory stage and thus impractical for use in industry. They further indicated that research efforts should focus on bringing theoretical constructs to a level at which they can be effectively deployed in practice. Obstacles to this are the technical challenges of organizing and managing knowledge, and the design challenges associated with developing useful and usable systems so that there are identifiable benefits to the product teams that use them.

A number of design rationale techniques are offered in the literature for supporting the traceability of functional architectures of products, i.e. the derivation of design requirements[5] from design parameters [**18**, **28**, **57**, **72–74**]. For example, Bracewell *et al.* [**74**] developed a software tool that enables the capture and documentation of engineering design rationale during the design process. However, these techniques do not provide a comprehensive traceability scheme to support the derivation of design requirements from stakeholder needs.

In conclusion, the aforementioned research efforts provide powerful methods and tools for capturing, documenting, and tracing the reasoning behind concrete technical design decisions. However, such efforts do not deal with the reasoning behind the intents of customers and other stakeholders.

3.1.3 Requirements connectivity

It has been widely acknowledged [**57**, **59**, **75–77**] that design engineers can deliver desirable products to customers, in a systematic rather than trial-and-error manner, only if they focus on customer requirements throughout the design process. Furthermore, according to Gerst and others [**78**], effective linkage of product innovation to customer requirements contributes to the efficient development of new products.

McAdams, Stone, and Wood [**79**] highlighted that analysis of products at a functional level allows for connections between customer needs, function, and form to be explicit. They developed a method for determining the importance of interdependent functions in groups of products. However, the strength of their approach lies in the identification of subfunctions rather than in the connections between customer needs and product functionality. Identification of such connections is limited to the use of weights on customer needs for determining their functional importance.

Harding *et al.* [**57**] developed a market-driven design system that enables a design team to use customer requirements information for the development of design requirements. They argue that '... the purpose of this system is to interpret raw, imprecise market information into clearly defined, genuine customer requirements [that] provide an accurate basis from which design engineers can produce a design specification'. However, their system is more effective for assessing the importance of customer requirements to potential design requirements than providing a systematic method for deriving design requirements from a set of customer requirements.

In conclusion, research work in this category does not address the explicit linking and aligning of requirements of stakeholders to corresponding design requirements. The significance of the aforementioned issue is emphasized by the research findings of Khurana and Rosenthal [**58**], according to which the greatest success for enterprises stems from the adoption of a holistic approach to effectively linking business strategy, product strategy, and product-specific decisions.

3.1.4 Approaches to requirements management

Research efforts in this category can be grouped into three subcategories: requirements patterns and reuse, requirements modelling, and the design and implementation of requirements management processes.

Requirements patterns and reuse – Tseng and Jiao [**73**] introduced an approach to requirements management that is based on identifying patterns of functional requirements from existing products. However, their approach does not support effectively the development of new innovative products. This is because it requires preliminary functional requirements to be given by the customer, and because innovative products usually have unique functional architectures. Chen, Khoo, and Yan [**80**] developed a prototype system that combines the application of a laddering technique for the elicitation of customer requirements with a neural network based on adaptive resonance theory for their evaluation. The underlying assumption of the laddering technique is that customers know their requirements. However, the validity of this assumption is questionable [**77, 81, 82**].

Requirements modelling – Zhang and Xiong [**83**] propose the modelling of product requirements based on product structures and product development processes. Although their model considers a number of stakeholder requirements, it neither considers relationships between stakeholder requirements, nor their relationships to design requirements. Jiao and Tseng [**72**] propose an information model for requirements management, but the mapping of customer requirements to product specifications (i.e. design requirements) is oversimplified; it is modelled through a many-to-many relationship (referred to as 'map to'). The model does not provide details on the relationships encapsulated within the 'map to' relationship. McKay, de Pennington, and Baxter [**84**] propose a representation scheme for product specifications that focuses on the realization of an electronic product specification. They describe a product data model that supports the description of mechanical product specifications, but the model does not provide details on the derivation of product (design) requirements.

Design and implementation of requirements management processes – Kaulio *et al.* [**77**] proposed and validated a set of five principles for the effective design and implementation of a new process for managing customer requirements. However, they did not deal with the development of methods that could effectively satisfy the established principles. Instead, they referred to currently deployed methods (e.g. QFD, affinity diagrams). Maurer and Cantabery [**85**] propose a practical approach for managing requirements through a combination of the principles of systems engineering and QFD. However, their approach suffers from the drawbacks of QFD [**48**, **86**, **87**] and the insufficiencies of common systems engineering processes [**81**, **88**, **89**].

In conclusion, research work into the management of requirements is either focused on managing aspects of customer requirements or on managing the evolution of design requirements. The proposed information models or processes of requirements management do not deal with the management of customer/stakeholder requirements and their relationships with derived design requirements in sufficient detail. As a consequence, for example, it is not possible to trace the evolution of a given customer requirement to a constraint imposed on one or more functional requirements.

4 THE SYSTEMATIC DERIVATION OF DESIGN REQUIREMENTS FROM STAKEHOLDER NEEDS

This section describes the main processes/activities in the analysis of stakeholder requirements

Table 1 Concepts used in this research and their definitions

Concept	Concept definition
Requirement	According to the IEEE standard (Std 1220–1994) a requirement is 'a statement identifying a capability, physical characteristic, or quality factor that bounds a product or process need for which a solution will be pursued'.
Product requirement	A product requirement is a requirement that relates to the realization of an electromechanical product. Product requirements are acquired in terms of stakeholder and/or design requirements. Specifically, corporate analysis and market research are the prime activities that result in collection of customer and other stakeholder requirements, in the context of market-driven enterprises[22]. On the other hand, contractual agreements are usually the source of stakeholder and design requirements, in the context of industry-driven enterprises[23]. This paper deals with the former.
Expressed stakeholder requirement	An expressed stakeholder requirement is a product requirement that expresses either a stakeholder requirement or a perceived solution. This implies that although a product requirement may be considered as a stakeholder requirement, it may only describe a perceived solution to a stakeholder requirement. In this case, it has to be restated to describe its associated stakeholder requirement instead.
Perceived solution	A perceived solution is an expressed stakeholder requirement that describes a specific design parameter of a physical or non-physical product (i.e. service) that may satisfy one or more stakeholder requirements.
Stakeholder requirement	A stakeholder requirement is an expressed stakeholder requirement that relates to a need and/or a want of a customer or other stakeholder[24]. The success or failure of prospective solutions is evaluated, among other things, against the satisfaction of a set of stakeholder requirements.
Stakeholder need (SN)	A stakeholder need is a stakeholder requirement that indicates a capability void and its expression pertains to the intents of a stakeholder. As such, a stakeholder need is independent not only of any prospective solution, but also of the activities associated with the realization and utilization of such solution.
Stakeholder attribute (SA)	A stakeholder attribute is a stakeholder requirement that indicates an inherent capacity and its expression pertains to the anticipated life cycle operational feasibility[25] that the prospective solution shall demonstrate. As such a stakeholder attribute may be partially dependent both on a prospective solution and on the activities associated with the realization and utilization of such solution.
Mapping relationship	A mapping relationship is a relationship that indicates a dependency between a stakeholder need and a stakeholder attribute.

which form a part of the research framework shown in Fig. 2. Table 1 defines the concepts required for the purposes of this paper; apart from the mapping relationship, all of these concepts have been introduced by Agouridas *et al.* [**90**]. Next, Fig. 7 gives an overview of an IDEFØ activity model for the systematic derivation of design requirements from stakeholder needs. An analysis of the activity model highlighted the need for the identification, documentation, and graphical representation of mapping relationships between stakeholder needs and stakeholder attributes. This need and how the MoRal$_{TM}$ responds to it are outlined in section 4.1. Section 4.2 outlines the key characteristics of MoRal$_{TM}$.

4.1 Analysis of activity model – the need for the motivational rationale traceability matrix (MoRal$_{TM}$)

The first-level decomposition of the IDEFØ activity model contains three activities.

1. Activity A1: revise product requirements.
2. Activity A2: analyse stakeholder requirements.
3. Activity A3: derive design requirements.

Figure 8 shows these activities and key information flows between them. A description of Activity A1 can be found in Agouridas *et al.* [**90**]. This paper focuses on aspects of Activity A2.

The activity model is built upon an information model that describes relationships between different types of stakeholder and design requirements [**1**]. Activity A2 focuses on the analysis of stakeholder requirements. Stakeholder needs and stakeholder attributes are two types of stakeholder requirements that are related through mapping relationships. Identification and documentation of such relationships (including their attributes) are key to the traceable and systematic derivation of design requirements from stakeholder needs. Hence, issues associated with the effective completion of Activity A2 are:

(a) the elaboration of the mapping relationship between stakeholder needs and stakeholder attributes;
(b) the determination of the motivational rationale for stakeholder needs and stakeholder attributes;
(c) the documentation and presentation of the results of tasks (a) and (b).

Consideration of these issues in conjunction with a review of related literature led to the development of the MoRal$_{TM}$. The following paragraphs compare and contrast MoRal$_{TM}$ with the literature survey found earlier in section 3 and with significant other design rationale methods.

In the literature, terms such as design rationale [**23**, **34**, **67**, **74**] and requirements rationale [**22**] tend to indicate approaches for tracing design decisions to solutions and design requirements

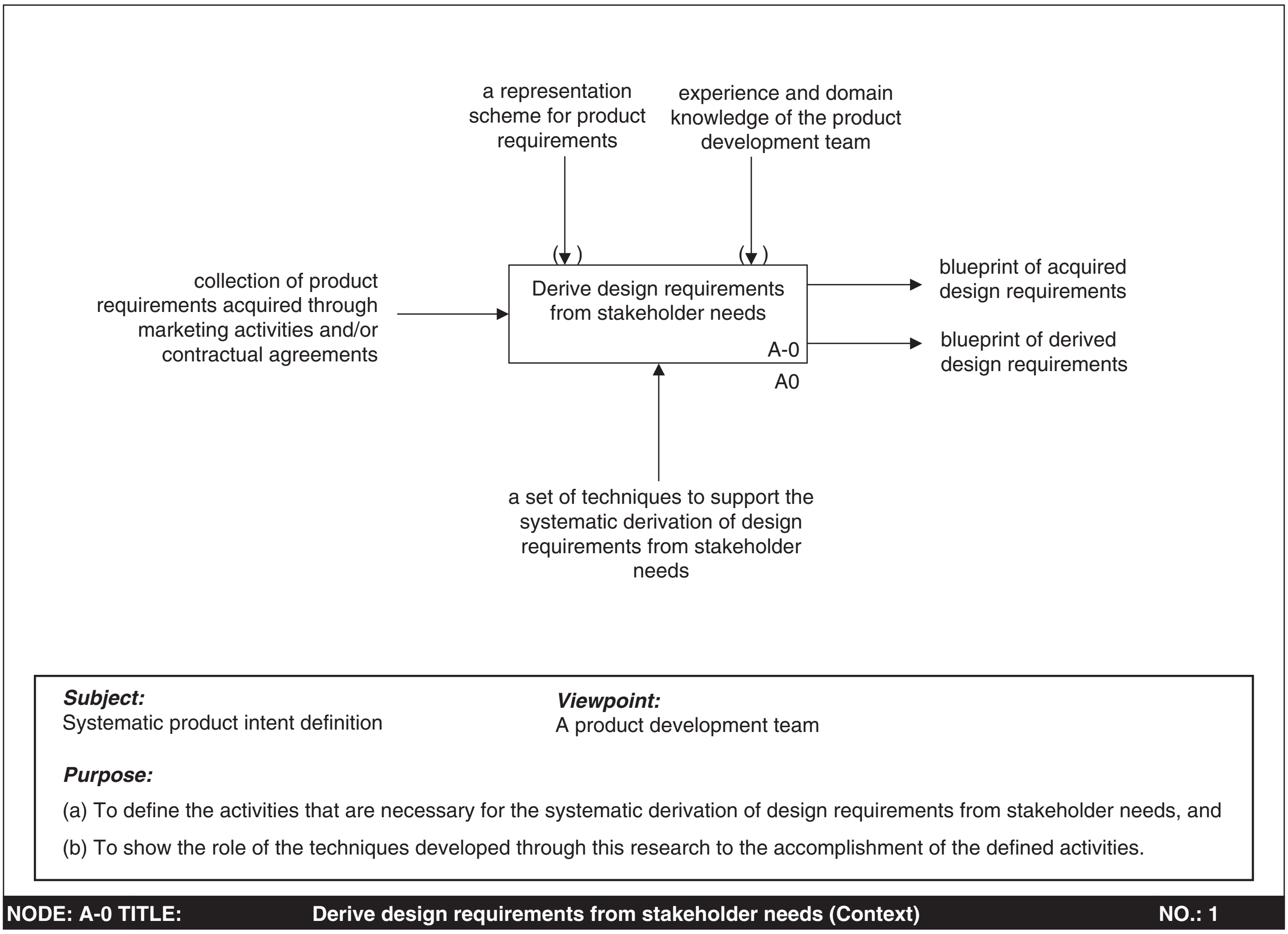

Fig. 7 IDEFØ diagram of activity A–0: derive design requirements from stakeholder needs (Context). (Source: Agouridas [**1**]) (NB: acquired design requirements are associated with contractual agreements, which are not the focus of this paper)

respectively. Design rationale is a means of representing design reasoning for the purposes of guiding decision making, keeping track of developed designs and accumulating knowledge about potential solutions [**34**, **74**, **91**]. In a similar way that design rationale refers to why a solution has been chosen or developed, an approach for eliciting design requirements from customer requirements has been suggested by Sutcliffe [**22**]. However, this approach refers only to a systematic combination of techniques for eliciting customer needs and attributes based on prototypes and questionnaires and not to a systematic approach for analysing and translating them to design requirements.

Other approaches refer mainly to the source and to the contributor aspects of stakeholder requirements definition [**25**, **26**]. For example, Gotel and Finkelstein [**25**] emphasize the consideration of so-called 'pretraceability' [**20**, **24**, **92**] and suggest the use of contribution structures for capturing the rationale of stakeholder requirements. Such structures support the identification of interrelationships between humans involved in the definition of stakeholder requirements. In his work towards the establishment of reference models for requirements traceability, Ramesh [**93**] observes that the rationale of stakeholder requirements is usually captured as notes; he also observes that the detailed capture of such rationale is impractical because it is a labour intensive and expensive process with few tools to facilitate the process.

For the purposes of this research, the rationale behind stakeholder requirements that underlies the derivation of design requirements throughout the life-cycle of a product stems primarily from motivational triggers that customers and other stakeholders have for satisfying one or more of their needs (see also section 1). The term 'motivational rationale' is introduced to refer to this type of rationale. In the case of new electromechanical consumer products, which are of the focus of this paper, determination

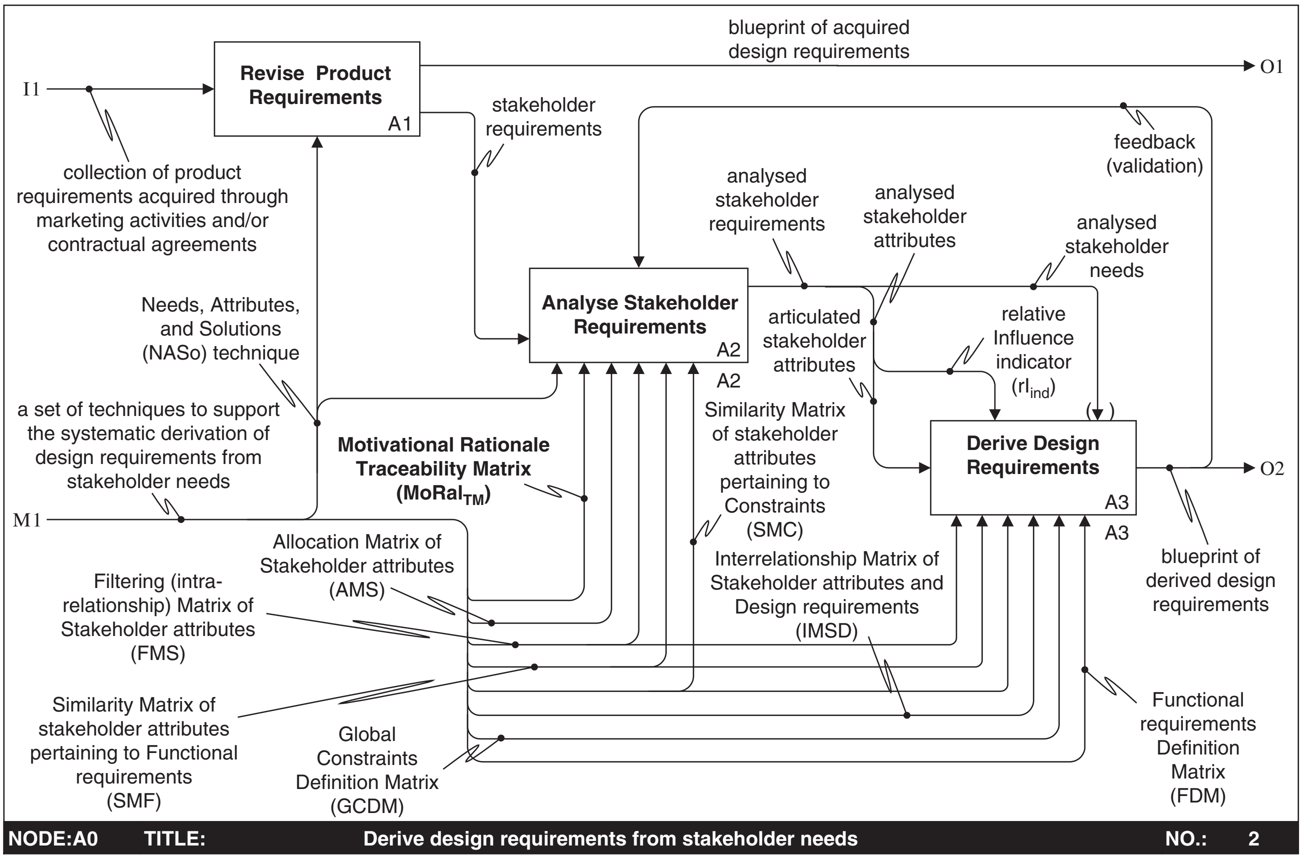

Fig. 8 IDEFØ diagram of the decomposition of activity A0: Derive design requirements from stakeholder needs. (Source: Agouridas [**1**])

and traceability of the motivational rationale behind stakeholder requirements enhance the delivery of products of requisite quality because[6]:

(a) they support the derivation of design requirements from stakeholder needs;
(b) they enhance the product validation process by ensuring that the design parameters of the prospective solutions are aligned with all significant stakeholder needs and are demonstrably traceable to stakeholder intents.

$MoRal_{TM}$ was developed to support the systematic derivation of design requirements from stakeholder needs that fully capture all significant stakeholder needs and makes them traceable to stakeholder intents. To this end, $MoRal_{TM}$ is an intentional structure[7]. As shown in Fig. 9, its matrix structure is unique in that it features traceability of both the dependencies between stakeholder needs and stakeholder attributes, and of the motivational rationale that underlies them. With respect to the latter, both traditional approaches and current practice in the capture of design requirements rationale and establishment of traceability schemes deal with managing the traceability of design requirements once these have been derived, whereas $MoRal_{TM}$ provides traceability of the rationale *in the derivation of* design requirements[8] from stakeholder needs (i.e. of the motivational rationale). In effect, $MoRal_{TM}$ contributes to the pretraceability[9] aspect of requirements engineering and management processes.

The effectiveness with which product development teams communicate and collaborate has been acknowledged as a significant factor in improving design practice. Schrage [**94**] put forward the concept of a 'shared space'[10] as a key to effective team collaboration. Based on this, $MoRal_{TM}$ can be considered as a shared space, not only for identifying and documenting, in a graphical way, relationships between stakeholder needs and attributes, but also for capturing the motivational rationale that underpins these needs and attributes. As such, $MoRal_{TM}$ can promote interaction among the members of a product development team, and support them by augmenting their awareness and understanding of issues that relate to value characteristics, as opposed to specific design parameters, of prospective products. This is key for deriving solution-independent design requirements from stakeholder needs and

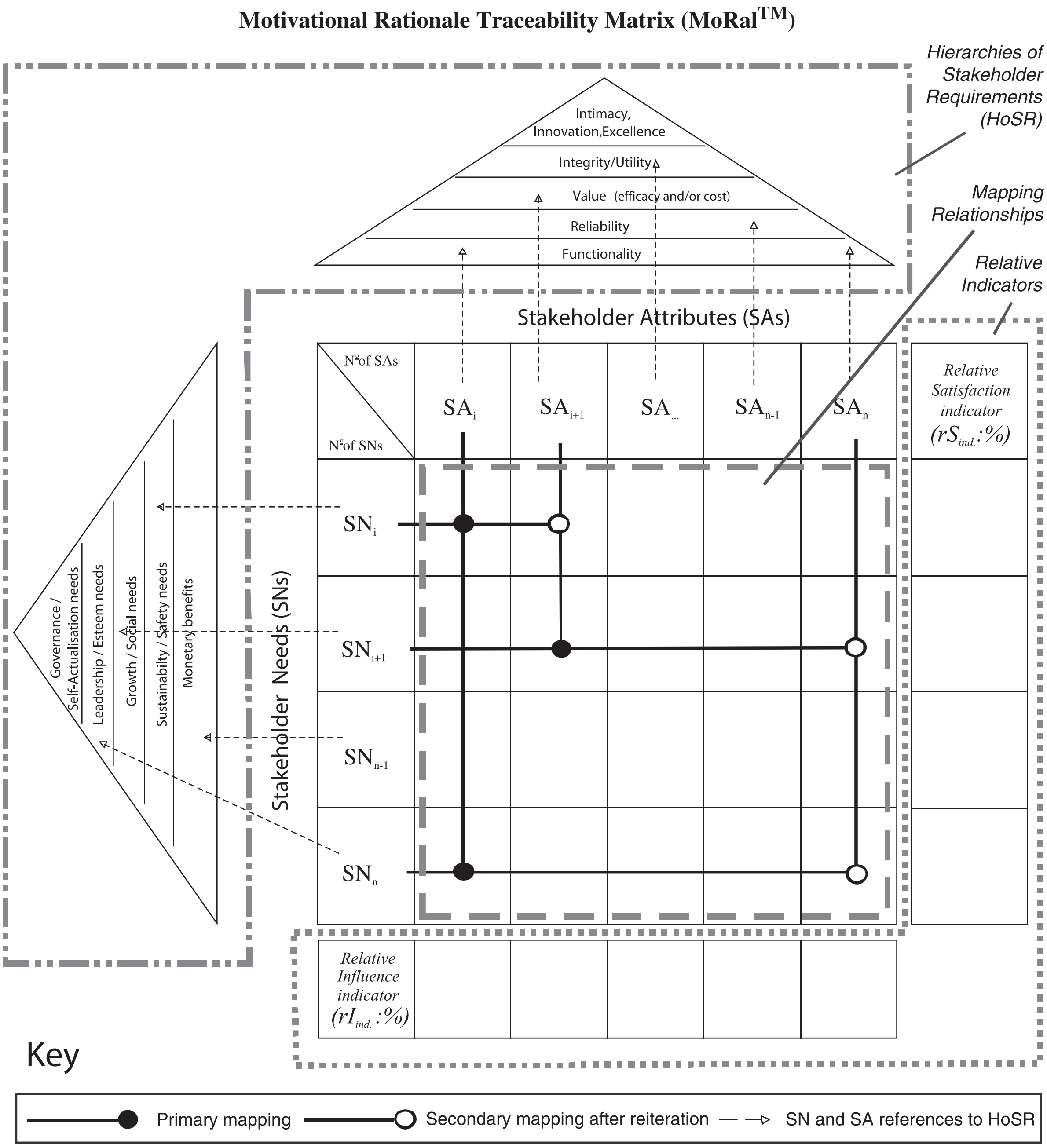

Fig. 9 MoRal$_{TM}$ (graphical version)

a requisite task for the development of new, innovative and user-centred products. Lindgaard *et al.* [**95**] highlighted that, although it is widely known and accepted in user-centred design that iterative design proceeds before all requirements are fully understood (e.g. [**96**]), the details of how to proceed in the midst of evolving requirements are unclear. MoRal$_{TM}$ brings together, in an illustrative[11] way, information useful to product development teams and managers in making informed decisions on their evaluation of new business and/or product opportunities. In other words, it supports top-down (or a systems approach) strategy-to-concept analysis.

4.2 Key characteristics of MoRal$_{TM}$

As depicted in Fig. 9, MoRal$_{TM}$ has three main parts: the mapping relationships, the hierarchies of stakeholder requirements (HoSR), and the relative indicators.

4.2.1 Mapping relationships

The definition of the term 'mapping relationship' is given in Table 1. Figure 9 labels the part of MoRal$_{TM}$ that is associated with the mapping relationships. There are two kinds of mapping relationship: primary and secondary.

Primary mapping relationships are strong associations between stakeholder needs (SNs) and stakeholder attributes (SAs). Such relationships are captured in the following way. Once an initial set of SNs and SAs have been established, each SN is mapped to at least one existing, or newly determined, SA that strongly satisfies this SN. In a similar way, each SA is mapped to at least one existing, or newly identified, SN that is strongly satisfied by this SA. In this way, an initial set of strong relationships or primary mappings between SNs and SAs, shown as solid bullets in Fig. 9, is established[12].

Secondary mapping relationships are weak associations between SNs and SAs. Such relationships are captured in the following manner. Once primary mappings are completed, an evaluation is carried out of potential mappings between each SN or SA and the established lists of SAs and SNs respectively. This allows for the capture of weaker relationships, or secondary mappings, shown with blank bullets in Fig. 9, between SNs and SAs.

It should be noted that the determination of mapping relationships takes place iteratively and involves the following tasks:

(a) existing SAs and SNs may be refined, merged or split, and/or
(b) new SAs may be determined, and/or
(c) new SNs may be identified.

In this way, a complete set of primary and secondary mappings between SNs and SAs is established. Iterations continue until the product development team feels confident with the established mappings.

4.2.2 Hierarchies of stakeholder requirements (HoSR)

An outline of Maslow's hierarchy of needs and a description of its application and modification to encompass stakeholder requirements in the context of commercial organizations and consumers are given in this section.

Maslow's hierarchy of needs [**97**] categorizes human needs across five levels, as shown in Fig. 10(a): physiological needs, safety needs, social needs, self-esteem needs, and self-actualization needs. Maslow suggests that these needs work in a hierarchy where the lower-order needs (physiological and safety) are dominant until satisfied, whereupon the higher-order needs come into operation.

It has been assumed, for the purposes of the reported research, that Maslow's hierarchy of needs can be applied to the early phases of the product development process. However, to be applicable here, Maslow's model had to be modified to encompass stakeholder needs (related to business/ consumer aims) and stakeholder attributes (related to product benefits). To this end, modification of the Maslow model led to the development of two

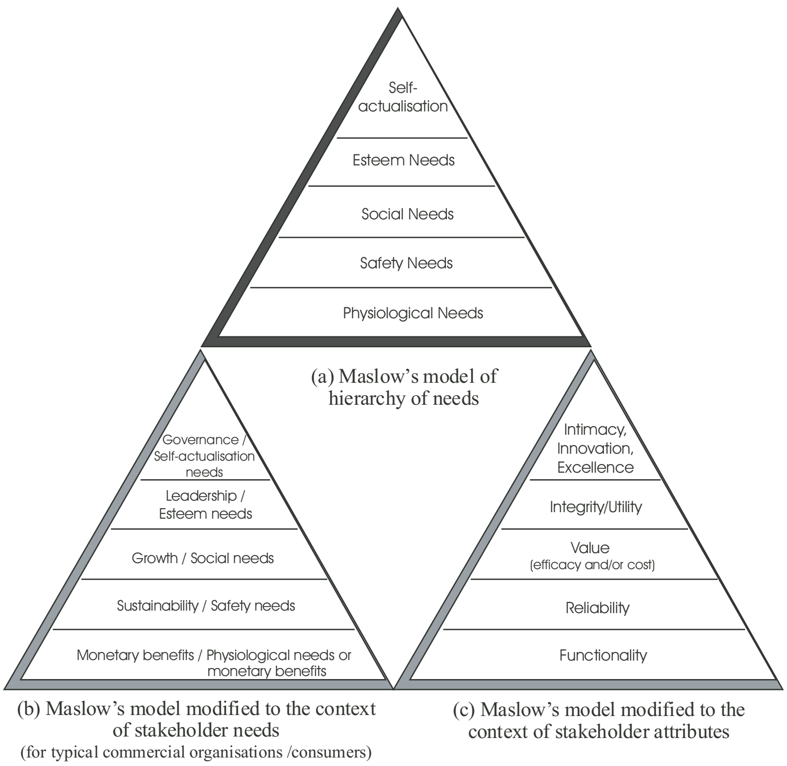

Fig. 10 Hierarchies of stakeholder requirements (HosR)

'hierarchies of stakeholder requirements' (HoSR); one for stakeholder needs and one for stakeholder attributes, as shown in Figs 10(b) and (c) respectively.

Modification of Maslow's hierarchy to the hierarchy of SNs (Fig. 10(b)) was informed by a case study carried out with an engineering company [**98**] and consideration of literature associated with corporate strategy [**99**]. Similarly, modification of Maslow's hierarchy to the hierarchy of SAs (Fig. 10(c)) was informed by a case study carried out with a consumer products manufacturing company [**52**], and consideration of literature associated with product marketing [**100**], product design [**101**], and product value [**102**].

The aim of developing the HoSR was to allow the capture of the motivational rationale for each stakeholder need (SN) and stakeholder attribute (SA). For this reason, the HoSR have been integrated into MoRal_{TM}. The capture of the motivational rationale for each SN and SA involves the determination of the appropriate level in the HoSR (pyramids in Fig. 9) for each SN and SA, as indicated through the use of dashed arrows in Fig. 9. As a result, each SN and SA 'carries' references that enable traceability of their motivational rationale.

4.2.3 *Relative satisfaction* (rS_{ind}) *and influence* (rI_{ind}) *indicators*

The establishment of primary and secondary mappings between SNs and SAs gives qualitative information on the way in which each SN is influenced by each SA and vice versa. Quantification of such information can further support a product development team in its task in that the resulting values can be used for a quick and informed appreciation of the importance of the mapping relationships, for each SN and SA, to the downstream activities of the product development process. To this end, two metrics have been developed and are presented below. These metrics are aligned with the principles of lean design thinking in that customers have what they want only when they require it [**29**, **30**]. Figure 9 shows how these metrics have been integrated into MoRal_{TM}.

1. The *relative satisfaction indicator* (RS_{ind}) is defined as the ratio of the total number of mapping nodes (i.e. primary and secondary) that correspond to a given SN ($\text{MNs}_{\text{tot. [SN]}}$), to the total number of stakeholder attributes (SAs_{tot})

$$rS_{ind} = \frac{\text{MNs}_{\text{tot.[SN]}}}{\text{SAs}_{\text{tot.}}}(\%) \tag{1}$$

The rS_{ind} indicates the degree of dependency (or interrelationship) among the total number of SAs (SAs_{tot}) relative to a given SN and is expressed as a percentage (%). In particular, if:

(a) $\text{MNs}_{\text{tot.[SN]}} = \text{SA}_{\text{tot.}}$, then $rS_{ind} = 100\%$, meaning that all of the listed SAs are mapped to the given SN;
(b) $\text{MNs}_{\text{tot.[SN]}} = 0$, then $rS_{ind} = 0\%$, meaning that there are no mappings to at least one SA for the given SN[13].

Such information equips a product development team with awareness[14] of the potential complexity involved in fully satisfying a given SN.

2. The *relative influence indicator* (RI_{ind}) is defined as the ratio of the total number of primary mapping nodes that correspond to a given SA ($\text{PMNs}_{\text{tot.[SA]}}$), to the total number of mapping nodes ($\text{MNs}_{\text{tot.[SA]}}$), which also correspond to this SA

$$rI_{ind} = \frac{\text{PMNs}_{\text{tot.[SA]}}}{\text{MNs}_{\text{tot.[SA]}}}(\%) \tag{2}$$

The rI_{ind} indicates the degree of influence, in terms of primary mappings, of a given SA to the derivation of corresponding design requirements and is expressed as a percentage (%). In particular, if:

(a) $\text{PMNs}_{\text{tot.[SA]}} = \text{MNs}_{\text{tot.[SA]}}$, then $rI_{ind} = 100\%$, meaning that all the mappings to a given SA are primary ones;
(b) $\text{PMNs}_{\text{tot.[SA]}} = 0$, then $rI_{ind} = 0\%$ meaning that either all the mappings to a given SA are secondary ones (i.e. no primary mappings are present at all) or they are not mappings at all[15].

It should be noted that the values associated with the rS_{ind} inform a product development team on the influence[16] of a given SA from the design point of view, not the influence stemmed from stakeholder perceptions. The latter can be identified and measured through analysis of the stakeholder preferences by deploying techniques such as conjoint analysis [**101**]. Ideally, these two kinds of influence should coincide for successful products to be developed.

5 APPLICATION OF MORAL_{TM}

In this section, the main characteristics of MoRal_{TM} are illustrated with a case study drawn from the power production sector. In addition, the case study allows for an in-depth application and evaluation of the IDEFØ activity model shown in Figs. 7 and 8. Since this paper is focused on Activity A2 depicted in Figs. 7 and 8, and more precisely on MoRal_{TM}, this section demonstrates its application for the development of a new product. For completeness, Activities A1 and A3 are also outlined.

5.1 Description of the application of MoRal$_{TM}$ against the research methodology

Sections 5.1.1 to 5.1.3 present a case study against the main elements of the research methodology described in section 2. Specific details of industrial significance have been edited from this paper, but this does not impact the value of its findings. A discussion of the main points from the application of MoRal$_{TM}$ is given in section 5.2.

5.1.1 Real-world problem situation

The research team had the opportunity to apply, evaluate, and refine the research framework by working on a case study provided by Rolls-Royce plc, the power for land, sea, and air company. As part of its core business, Rolls-Royce brings to market large power systems. Such products require material investments to develop and support and their development requires careful planning. Rolls-Royce has a strong track record in the delivery of such large power systems to its core markets. In this instance, the case study is focused on a microturbine for commercial use to meet the demands of emerging distributed power needs. This is a much less complex product than Rolls-Royce's large power systems. As a result, it was postulated that Rolls-Royce may need to have a supplemental approach to its already strong and credible new product introduction processes to ensure that it would capture fully stakeholder needs and attributes. A small team had identified that satisfaction of customer needs, as well as consideration of competitive products, were the most critical success factors in the development of a microturbine for distributed power.

5.1.2 Structured experience

The research team gathered data about the real-world problem situation from documentation provided by the product team, a review of literature on power deregulation, identification of microturbine and other energy solutions of competitors, and semistructured interviews with key members the product team[17]. The data extracted from these activities were further augmented through a series of three follow-up teleconferences and eventually informed the execution of Activity A1 (see Fig. 8). The following paragraphs describe the outcome from this activity.

Activity A1: revise product requirements – Completion of activities for data gathering and elicitation resulted in 377 product requirements (PRs) for a micro-energy solution. From these, 75 of the most important stakeholder requirements (SRs), representing all the aspects[18] of Solution Space™ [**52**, **103**], were selected. Selection of these SRs was based on the experience and appreciation of all team members (i.e. research and product teams). The situation was that the majority of the selected SRs were both discursive and solution-dependent. The following are three common problems that arise from such situations.

1. Product teams run the risk to misinterpreting and biasing the stated SRs.
2. Product teams have difficulty in evaluating the satisfaction (or not) of SRs because they often have a poor syntax structure and their associated metrics are missing.
3. Product teams are impeded in developing innovative solutions because the stated solution-dependent SRs are usually taken for granted and not challenged.

To cope with the above-listed problems, tools and techniques are required to support the revision of collections of SRs to form a coherent collection of clearly articulated SRs. This was achieved through the use of the NASo (needs, attributes, solutions) technique [**1**]. This resulted in 120 SRs, and thus augmented the total number of PRs to 422. For example, during the application of Solution Space™ [**52, 103**], the manufacturer's requirement of 'provision of a microturbine' was captured and classified as design for customers (DFC). Application of the NASo technique showed that this was a solution-dependent stakeholder requirement. The underlying stakeholder requirement was that of 'provision of a solution to ensure uninterrupted power supply'.

Activity A2: Analyse stakeholder requirements – The first-level decomposition of Activity A2 is given in Fig. 11. It contains the following activities:

(a) A21: elaborate mapping relationship between stakeholder needs and stakeholder attributes;
(b) A22: determine motivational rationale for stakeholder needs and stakeholder attributes;
(c) A23: articulate stakeholder attributes.

The following subsections detail activities A21 and A22 and show how the characteristics of MoRal$_{TM}$ support their completion.

(a) *Activity A21: Elaborate mapping relationships between stakeholder needs and stakeholder attributes* – This activity deals with the mapping of SNs to SAs and vice versa. This requires that the acquired stakeholder requirements have already been revised and classified to SNs and SAs. Agouridas *et al.* [**90**] described how this task can be accomplished through consideration of the concept definitions

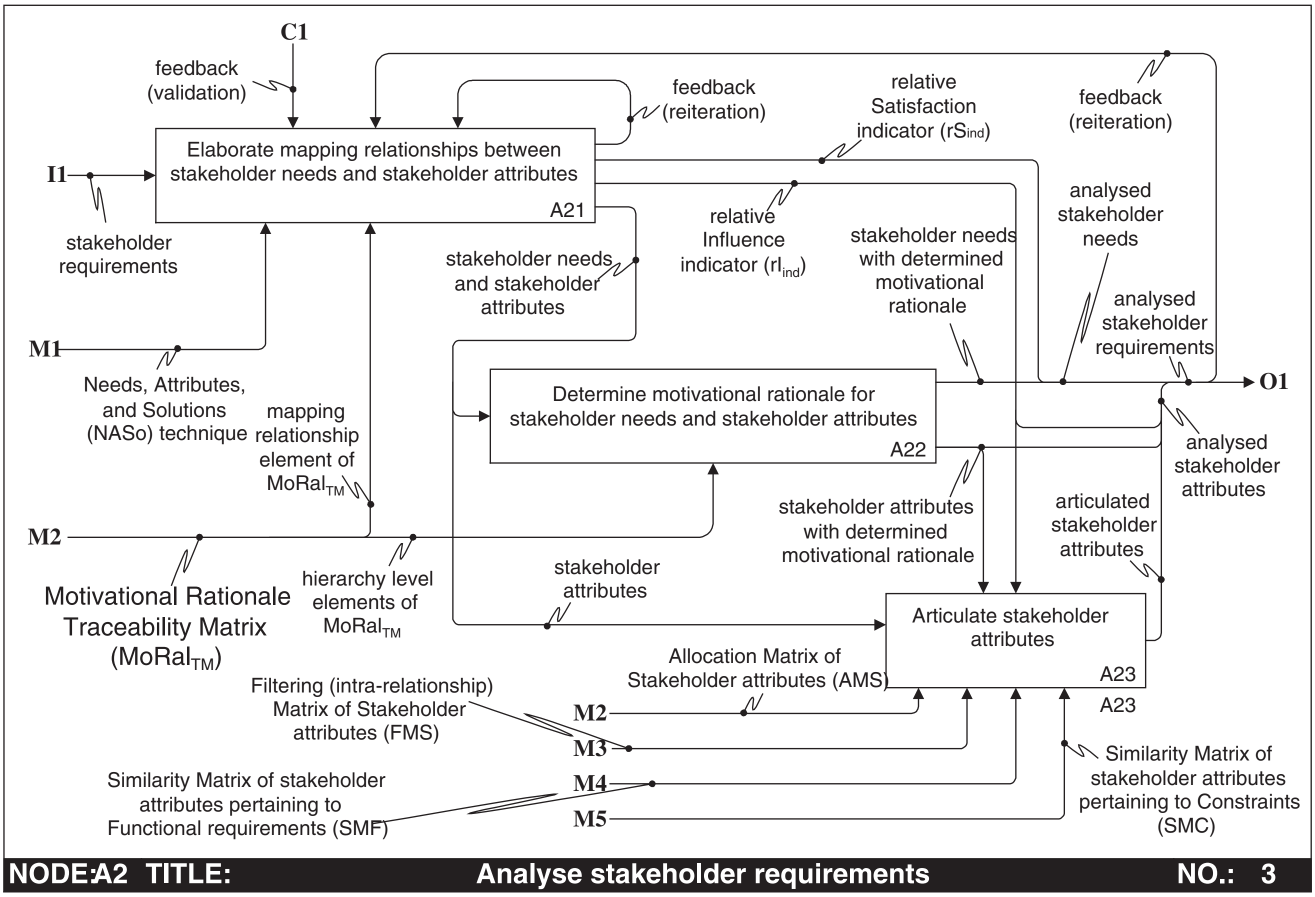

Fig. 11 IDEFØ diagram of the decomposition of activity A2: analyse stakeholder requirements

presented in Table 1. It should be noted that in-depth determination of SNs and SAs entails the analysis of stakeholder intents together with subsequent identification and detailed analysis of the antecedent states of those intents [**1**, **63**]. In addition, one should remember that an antecedent state constitutes a necessary condition for another state to be real [**63**]. The NASo technique [**1**, **104**] is a means of supporting this task. However, analysis of this technique is not the focus of this paper.

Mapping relationships – the selected 120 SRs were expressed initially as 110 SAs, and as 10 SNs. For example, the stakeholder requirement of 'uninterrupted power supply for critical instruments and operating theatres' (where the stakeholder is the customer) was expressed as a stakeholder attribute (SA). This completed the first task required for the activity of elaborating mapping relationships between SNs and SAs.

The second task involved two steps. First, it involved the determination of relationships, in terms of primary and/or secondary mappings, between SNs and SAs. Second, it involved the identification of SNs and the determination of SAs that had neither been captured during the product requirements gathering and elicitation activities, nor during the application of the NASo technique. For example, Fig. 12 shows that the stakeholder attribute 'SA-5: uninterrupted power supply for critical instruments and operation theatres' led to the identification of the stakeholder need 'SN-5(i5)[19]: to be sure of continuous operation of a surgery-intensive hospital with respect to power supply'; a primary mapping was determined for the relationship between SN-5(i5) and SA-5. This augmented the number of SNs from 10 to 30 (i.e. 20 additional SNs were identified by SAs), and, consequently, the total number of SRs from 120 to 140 and of product requirements from 422 to 442 respectively. All the above tasks informed the mapping relationships part of the $MoRal_{TM}$ structure shown in Fig. 12.

(b) *Activity A22: Determine motivational rationale for stakeholder needs and stakeholder attributes* – This step deals with the determination of the motivational rationale for each SN and SA. This requires the establishment of references to the hierarchies of stakeholder requirements. For example, as shown in Fig. 12, references to the functionality level of the HoSR for SA-5 and to the sustainability level of HoSR for SN-5(i5) were made, respectively.

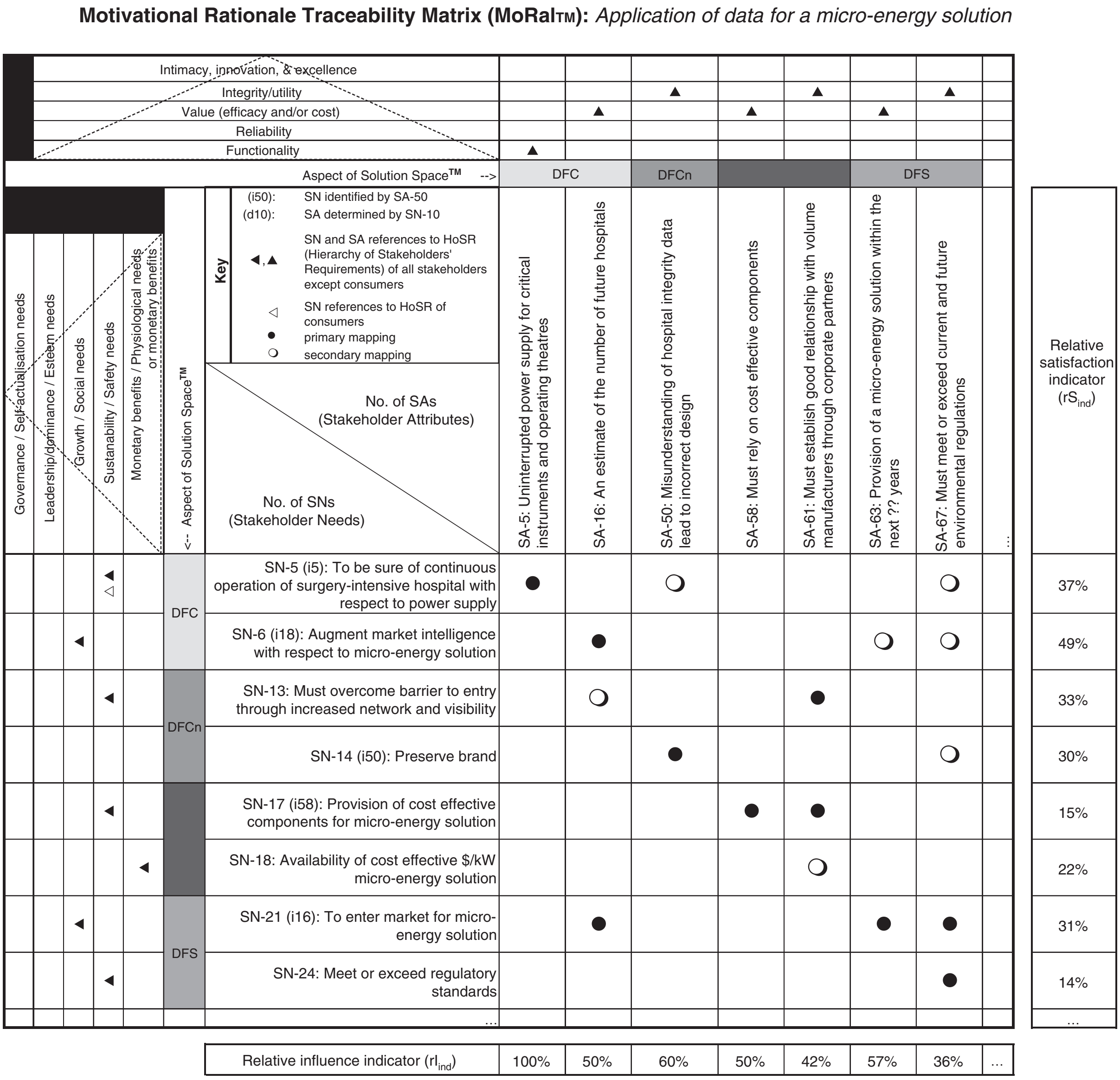

Fig. 12 A part from the MoRal$_{TM}$ developed for the micro-energy solution study (spreadsheet version – the aspects of the Solution Space^{TM} have been incorporated (NB: values of the relative indicators relate to the overall MoRal$_{TM}$))

The motivational rationale of the established 30 SNs and 110 SAs was determined based on the experience of the team members. Completion of the activity was supported by the HoSR part of MoRal$_{TM}$, as shown in Fig. 12.

Relative satisfaction (rS_{ind}) and influence (rI_{ind}) indicators (case study application) – the captured qualitative data of the mapping relationships were quantified through application of the metrics of rS_{ind} and rI_{ind}. For example, the value of rI_{ind} for 'SA-78: Provision of a high reliability micro-energy solution' was 100 per cent. This informed the product development team that 'SA-78' had only primary mappings to corresponding SNs and therefore its influence to the design of the product would be of major importance. Drawing from another example, rS_{ind} in this instance, 'SN-37: Remote access to micro-energy solution for total control' had a value of 9 per cent. This informed the product development team that only the 9 per cent of the total number of the established SAs were involved with the satisfaction of 'SN-37'. Furthermore, this value highlighted the importance of realizing the SAs associated with the given SN (i.e. in this case 'SN-37') in order for this be satisfied. Figure 12 shows only a part of the values associated with rS_{ind} and rI_{ind}, respectively.

Prompted from the above example, one of the primary-mapped SAs related to 'SN-37' was 'SA-33: Total internet-based customer relationship (long term)' with an rI_{ind} of 67 per cent. Consideration of rS_{ind} in conjunction with rI_{ind} for the given pair (i.e.

Table 2 A part from the blueprint of design requirements derived for the micro-energy solution study (NB: Definition of the blueprint of design requirements was informed by work on a functional basis carried out by Hirtz *et al.* [**105**])

Functional requirements definition matrix (FDM)											
Levels of specification in a functional basis			*Functional requirements and associated global constraints (blueprint of design requirements)*								
Input from IMSD						*Input from AMS*					*Input from IMSD*
Functional terms statements	Expressed as	**Functional class statements**	Expressed as	**Statements of functional requirements (FRs)**	Verified by	**PcRs (performance requirements)**	Classified as	**PrRs (priority requirements)**	**ImRs (importance requirements)**	Associated with	**Global constraints**
FR_2: Supply electric current for hospitals' needs		FR_2: Provision + electrical energy		FR_2:The micro energy solution shall provide electrical energy hospitals' needs		e.g. Max. time to provide required electric current?		Mandatory	None		e.g. Ct-2: the micro-energy solution shall ensure uninterrupted power supply for surgery-intensive hospitals' needs
...		...		...		...		...	...		...
FR_8: Regulate, and/or change, and/or stop, electric current, heat, and mixture material; AND sense, and/or indicate, and/or process, auditory, olfactory, tactile, visual, analog, and discrete signals		FR_8: Control magnitude + electrical energy		FR_8:The micro-energy solution shall control the magnitude of electrical energy		??		Mandatory	None		e.g Ct-9: the intelligent control systems of the micro-energy solution shall be accessed through the internet
		FR_{10}: Control magnitude + thermal energy		FR_{10}:The micro-energy solution shall control the magnitude of thermal energy		??		Optional	None		e.g Ct-9: the intelligent control systems of the micro-energy solution shall be accessed through the internet
		FR_{11}: Control magnitude + mixture material		FR_{11}:The micro-energy solution shall control the magnitude of the mixture material		??		Mandatory	None		e.g Ct-9: the intelligent control systems of the micro-energy solution shall be accessed through the internet
		FR_{12}: Signal + status signals		FR_{12}: The micro-energy solution shall signal status signals		??		Optional	Key		e.g Ct-9: the intelligent control systems of the micro-energy solution shall be accessed through the internet
		FR_{13}: Signal + control signals		FR_{13}: The micro-energy solution shall signal control signals		??		Optional	Key		e.g Ct-9: the intelligent control systems of the micro-energy solution shall be accessed through the internet

*Note: Flows may be expressed by a primary flow term (e.g. energy), or by a secondary or tertiary flow term + a primary flow term (e.g. thermal + energy). Functions are expressed in terms of secondary or tertiary function terms only (e.g. regulate).

'SN-37' and 'SA-33'), gave the values of rS_{ind} = 9 per cent and $rI_{ind} = 67$ per cent, respectively. From these, it could be demonstrated that their relationship was important not only because of their primary mapping but also for the following reasons:

(a) 'SNs37' was satisfied by a small percentage of SAs ($rS_{ind} = 9$ per cent, i.e. reduced dependency);
(b) 'SAs-33' had a high percentage of influence to the later stages of the design of the product (rI_{ind} = 67 per cent, i.e. increased influence).

5.1.3 Activity A3: Derive design requirements

This section outlines, for completeness, only the outcome of Activity A3. Completion of Activity A2 informed the execution of Activity A3 that delivered the derived design requirements.

Table 2 gives a part from the blueprint of the derived design requirements. It should be noted that the exact determination of performance requirements (PcRs) for both functional requirements and global constraints proved challenging and in many cases was left incomplete (see question marks in Table 2). Two reasons for this were the lack of access to the diversity of the required information sources and the need to execute separate studies (e.g. technical and commercial) to acquire the necessary data.

5.2 DISCUSSION ON THE APPLICATION OF $MORAL_{TM}$

This section is associated with the inform relationship (shown as feedback arrow) of the research methodology shown in Fig. 2 (see also the last part of section 2). The discussion below is based on anecdotal evidence originated from the initial interaction with the participants during both the completion of the semistructured interviews and of the elaboration of $MoRal_{TM}$. Such evidence was further augmented through additional interaction with the managing director and the chief engineer through the follow-up teleconferences and the feedback comments received by them at the end of the case study (reflection on case study report).

The application of $\mathrm{MoRal}_{\mathrm{TM}}$, as part of the application of the IDEFØ activity model presented in Figs 7, 8, and 11, supported the product development team in gaining insights into the main challenges in realizing the micro-energy solution. For example, the large amount of the expressed SAs enabled the product development team to identify a number of SNs described in sections 4.2.1 and 4.3.2. The task of identifying SNs from expressed SAs proved beneficial for the product development team. In effect, it allowed them to deepen their understanding of the problem at hand. Specifically, insights were gained into product and commercial issues. Examples of product issues included accessibility, interfaceability, modularity (e.g. potential use of energy slice modules), and supportability required for the operational effectiveness of the micro-energy solution. Commercial issues included branding strategy linked with the delivery of small power packs that differed from that of the large power systems for which the team's business is known. $\mathrm{MoRal}_{\mathrm{TM}}$ allowed the members of the product development team to gain a common view on a variety of issues through the removal of misconceptions. Enablers of this were, in part, the tasks of expressing an SR either as an SN or SA and determining references to the hierarchies of stakeholder requirements (HoSR) for each SN and SA. For example, SN references to HoSR (i.e. relationships between SNs and HoSR) proved useful for linking strategic needs dimensions (pyramid levels in HoSR) with SNs. Further, SA references to HoSR (i.e. relationships between SAs and HoSR) proved useful for positioning design alternatives with respect to their competition in terms of technical and other product characteristics. It should be noted that competition related to technical and commercial SAs was not analysed adequately owing to insufficient information and time constraints. Similarly, issues related to volume manufacturing and supply chain management required further analysis, facts that the application of $\mathrm{MoRal}_{\mathrm{TM}}$ highlighted to the integrated project team.

The references to the HoSR allowed the product development team to improve its understanding of issues associated with the provision of a micro-energy solution through the determination of the motivational rationale for each SN and SA. That is, the use of $\mathrm{MoRal}_{\mathrm{TM}}$ helped the team to clarify and articulate crisply a number of points. For instance, the product development team was assisted in linking the power system *product* with the wider power *solution* as a whole. This assisted with the clarification of some of the stakeholder needs, through their referencing to the HoSR, which could otherwise not be easily defined. Secondly, because of the iterative nature of the $\mathrm{MoRal}_{\mathrm{TM}}$, insights gained through the determination of relationships between HoSR and all the SNs and SAs (i.e. SNs and SAs references to HoSR) may result in the re-examination of the established primary and secondary mappings between SNs and SAs. Thus, the determination of the HoSR references proved beneficial in supporting the product development team in augmenting its confidence in mapping relationships between SNs and SAs. Eventually, this assisted the team to derive design requirements that were aligned with stakeholder intents.

The use of the values of rS_{ind} in conjunction with rI_{ind} facilitated the task of determining or evaluating the mapping relationship (primary or secondary) for a given pair of SN and SA. For example, a reduced dependency (i.e. $rS_{ind}<20$ per cent) indicated that failure in delivering the involved SAs would increase the likelihood of failure to satisfy the given SN. On the other hand, an increased dependency (i.e $rS_{ind}>70$ per cent) indicated that success in satisfying a given SN would depend not only on the delivery of the involved SAs, but also on addressing the interrelationships among these SAs.

The application of $\mathrm{MoRal}_{\mathrm{TM}}$ can augment Rolls-Royce's good practice framework (as shown in Fig. 13) by providing the following.

1. Additional market insights with respect to explicitly analysed significant stakeholders, requirements. In general, this may support businesses to understand issues associated with the entry of adjacent or new markets.
2. Technical insights with respect to the development of solution-independent, high-level design requirements for a micro-energy solution. That is, the definition of the high-level functional requirements and their associated global constraints without the consideration of a specific solution. This would enable the OU (operational unit – see Fig. 13) to develop innovative concepts, and augment its confidence for making decisions associated with the feasibility of candidate micro-energy solution projects.
3. Business insights with respect to strategic management issues. Such insights would support decisions on prospective offerings (portfolio management) through listening to the market and explicitly analysing its requirements. This may benefit necessary interactions between CFBU[20] and OU (Fig. 13) with respect to the availability, and/or acquisition of capabilities required to

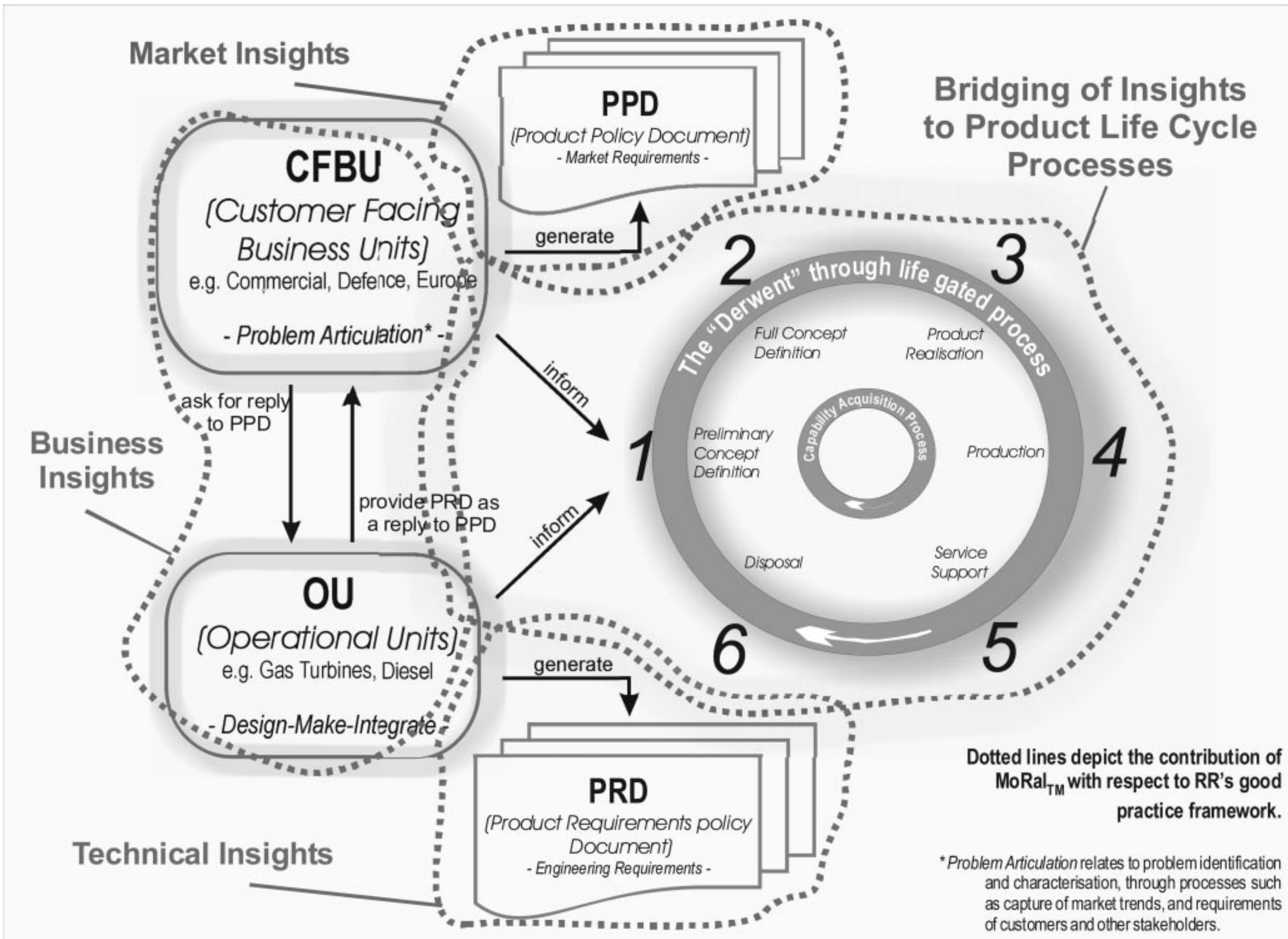

Fig. 13 Contribution of the application of MoRal$_{TM}$ to Rolls-Royce's good practice framework

deliver prospective offerings to the market. In other words, MoRal$_{TM}$ proved beneficial not only to identifying significant business issues and insights into the development of a micro-energy solution, but also to highlight little appreciated issues thereby de-risking the project.

4. Providing a rigorous methodology that bridges a multitude of insights, including market, business, and technical insights to inform the first stage of the Derwent[21] through life gated process (Fig. s13). In fact, MoRal$_{TM}$ allowed the comprehensive definition of the design requirements blueprint for a micro-energy solution. This blueprint provided a comprehensive basis upon which concepts could be scoped, developed, and reviewed.

In conclusion, MoRal$_{TM}$ has been a key in operationalizing the IDEFØ activity model for deriving design requirements from stakeholder needs. The application of MoRal$_{TM}$ allowed for these design requirements to be both aligned to stakeholder needs and traceable to stakeholder intents.

6 CONCLUSIONS

Product development processes require mediation between technological advances and stakeholders, expectations such as those of consumers, customers, and suppliers [**34**, **106**]. A significant barrier to fast and flexible product development is the lack of effective engineering design support tools for tracing design (technical) requirements through to stakeholder needs. This paper presented MoRal$_{TM}$ as a means of establishing such traceability. MoRal$_{TM}$ features engineering and traceability of the dependencies between stakeholder needs and stakeholder attributes, and of the motivational rationale that underlies them. It was shown through a case study that MoRal$_{TM}$ supports the derivation of design requirements that are aligned with customer and other stakeholder needs and are traceable to stakeholder intents.

A case study was carried out within Rolls-Royce plc and dealt with the design of a next-generation micro-energy solution. MoRal$_{TM}$ supported a product development team in augmenting its technical, market, and business insights through an analysis of stakeholder requirements supported by a traceability scheme for the early phases of the engineering design process. It was shown that MoRal_{TM} enables traceability of the motivational rationale that underlies the stakeholder requirements from which design requirements are derived. This is in contrast to existing approaches in requirements engineering and management, which enable traceability between stakeholder requirements and the design rationale that underlies the derivation of design requirements from design parameters (e.g. zigzagging in axiomatic design).

In conclusion, MoRal_{TM} enabled the product development team to augment its confidence in its decision-making process during the early phases of the engineering design process. Future research ought to investigate the integration of the characteristics of MoRal_{TM} with approaches used to assess customer needs [**59**] such as conjoint analyses [**101**] and needs patterns [**61**].

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APPENDIX 1

Notation

HoSR	hierarchies of stakeholder requirements
IDEFØ	integrated computer aided manufacturing (ICAM) definition method
$MNs_{tot.[SA]}$	the total number of mapping nodes that correspond to an SA
$MNs_{tot.\ [SN]}$	the total number of mapping nodes (i.e. primary and secondary) that correspond to an SN
$MoRal_{TM}$	motivational rationale traceability matrix
$PMNs_{tot.[SA]}$	the total number of primary mapping nodes that correspond to an SA
PR(s)	product requirement(s)
rIi	relative influence indicator (%)
rSi	relative satisfaction indicator (%)
SA(s)	stakeholder attribute(s)
SAs_{tot}	the total number of stakeholder attributes
SN(s)	stakeholder need(s)
SR(s)	stakeholder requirement(s)

APPENDIX 2

Endnotes

1 For the purposes of this research an intentional structure is the means by which an intricate web of intentional dependencies is represented. The latter are relationships among requirements of stakeholders at an intentional level (definition based on Yu and Mylopoulos [**26**]).

2 IDEF is an acronym meaning ICAM DEFinition, where ICAM is an acronym for integrated computer aided manufacturing. Developed by the US Air Force, IDEFØ is a method designed to model the decisions, actions, and activities of an organization or system.

3 Early research findings [**15**] showed that effective definition of design requirements calls for the consideration of the requirements of the most significant stakeholders. For this reason, and for the purposes of this research, the term of 'customer' has been changed to that of 'stakeholder' when reporting research on axiomatic design theory.

4 In-depth determination of customer needs entails analysis of their intents together with subsequent identification and detailed analysis of the antecedent states of those intents. An antecedent state constitutes a necessary condition for another state to be actual [**63**].

5 In this paper, the term 'design requirements' refers to both functional requirements and constraints (the latter is also referred to in the literature as non-functional requirements).

6 The research reported in this paper deals with the design and development of engineering products in the context of extended enterprise processes.

7 Recall that, for the purposes of this research, an intentional structure is the means by which an intricate web of intentional dependencies is represented. The latter are relationships among requirements of stakeholders at an intentional level (definition based on Yu and Mylopoulos [**26**]).

8 That is to say that MoRal$_{TM}$ deals with the traceability of the motivational rationale that underlies the stakeholder requirements from which design requirements are derived. On the other hand, traditional approaches and current practice to design requirements rationale deal with the traceability of the design rationale that underlies the design parameters from which design requirements are derived.

9 Pre-traceability approaches, such as those developed by Gotel and Finkelstein [**25**] and Yu and Mylopoulos [**26**], deal with the traceability of dependencies between stakeholders, not between stakeholder requirements.

10 A 'shared space' can be seen as a medium where people can manipulate and iterate ideas and representations of the ideas [**94**].

11 According to Lindgaard *et al.* [**95**], main problems in user-needs analysis include the decision as to where to begin and where to end the analysis, deciding how to document and present the outcomes to ensure seamless translation into user interface design, and completeness of the design.

12 Note the information model that describes the mapping relationship requires that each SN is mapped to an SA through at least one primary mapping and vice versa. If this is not the case, then new SNs and or SAs need to be determined accordingly.

13 Since MoRal$_{TM}$ requires at least one primary mapping between an SN and SA (see section 4.2.1), the above situation implies that either an SA must be determined for the given SN or the given SN must be withdrawn, or put aside for the current development cycle, because an SA cannot be determined for it. The latter case further implies either false identification of an SN or lack of know-how for addressing this SN; a fact that may direct a team to take action to address the given SN in a future product development cycle or even in the current cycle, if necessary. Therefore, a zero value acts as a warning to, and prompts for the attention of, the product development team.

14 The following scales have been defined for rS_{ind} to support awareness of a product development team:
(a) reduced dependencies (1–19 per cent);
(b) normal dependencies (20–60 per cent);
(c) increased dependencies (61–100 per cent).

15 Since MoRal$_{TM}$ requires at least one primary mapping between an SN and SA (see section 4.2.1), the above situation implies that either an SN must be determined for the given SA or the given SA must be withdrawn, or put aside for the current development cycle, because an SN cannot be determined for it. The latter case further implies either false determination of an SA or lack of an in-depth SNs identification and analysis for this SA; a fact that may direct a team to take action to carry out an in-depth analysis of the SNs associated with the given SA in a future product development cycle or even in the current cycle, if necessary. Therefore, a zero value acts as a warning to, and prompts for the attention of, the product development team.

16 Similar scales as those used for rS_{ind} apply to rI_{ind}:
(a) reduced influence (1–19 per cent);
(b) normal influence (20–60 per cent);
(c) increased influence (61–100 per cent).

17 The marketing and quality assurance directors participated in the semi-structured interviews only. The managing director and chief engineer, further to their participation in the semistructured interviews, were fully involved in the elaboration of MoRal$_{TM}$ (Activity A2) and the three follow up teleconferences. The completion of the four semistructured interviews and the elaboration of MoRal$_{TM}$ lasted for five days.

18 The four aspects of Solution Space™ are: design for customers (DFC), design for competition (DFCn), design for manufacture (DFM) and design for sustainability (DFS).

19 Note that (i5) indicates that SN-5 was identified from SA-5 and hence not collected through market research activities. Such indication is important for the robustness of the traceability scheme that is established.

20 CFBU: customer-facing business units.

21 Since completing this research, Rolls-Royce has extended the Derwent process. It is now simply known as the new product introduction process (NPI).

22 That is, enterprises that operate for the production of commercial and mass-produced products.

23 That is, enterprises that operate for the production of commercial and low-volume products (e.g. engineer-to-order enterprises undertaking one-off projects).

24 Examples of other stakeholders are those of consumers, manufacturers, suppliers, and regulatory agencies.

25 That is, functional and non-functional requirements.