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Research framework for development of building performance simulation tools for early design stages

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ABSTRACT

Recent research on identification of user barriers for the adoption of building performance simulation (BPS) tools indicates that architects wants to use the output from BPS to inform their decisions in the early design stage, but only if the BPS tools are conformed to fit their design practice. In this paper we therefore propose a research framework for the development of BPS tools conformed to fit common design practice in the early design stage. The proposed framework was constructed based on review of existing research methodologies in the area of BPS for informing decisions in the early design stage, and on review of methodologies used in other research fields, such as design research, social science, software development, and innovation research. The proposed research framework consists of four elements: 1) a *reflective researcher* who navigates the research activities and reflect on research methods, approaches and outcome; 2) a *framing* of the research to identify relevant theme, topic and research question of interest; 3) an iterative *workflow procedure* of planning, acting, observing and reflecting to generate a spiral of understanding, inspired by action research; and 4) a range of qualitative and quantitative research methods and approaches from the related research fields that could be applied continuously to seek and refine different solutions. The paper also reports on an application example which demonstrated that the framework is a helpful tool for systematic navigation and documentation of research activities and collection of data. Furthermore, the iterative nature of the framework continuously increases the researchers understanding of the underlying mechanisms of the design practice in early design stage enabling them to make better proposals for BPS tools that are conformed to fit common design practice in the early design stage.

1. Introduction

The European Performance Building Directive (EPBD) states that all new buildings constructed after 2020 should consume “near zero energy” [1]. This demand requires that design decisions in the early design phase are based on careful considerations about their potential impact on energy efficiency. However, design decisions also have to respect other issues such as thermal comfort, structural safety cost, aesthetics and other design issues. Choosing the appropriate combination of design options is therefore a complex task which requires the management of a large amount of information on the properties of design options and the simulation of their performance [2]. For thermal and daylight conditions, computer-based building performance simulation (BPS) tools like ESP-r [3], EnergyPlus [4] and Radiance [5] are ideal for this but they require expert knowledge and large amounts of input data for even the simplest simulation, rendering them impractical in the early design stages where information is scarce. Furthermore, these types of tools are not fit for evaluation of volatile design ideas and the rapid changes in design that characterizes the process of the early design stage. There are research-based efforts focusing on proposing procedures for enhancing efficient use of thermal and daylight building simulation tools for proactive performance prediction in the early design stage, e.g. Petersen [6], Attia et al. [7], and Gerber and Lin [8], to cite but a few. However, to our knowledge, there is no research-based evidence on whether any of such procedures are actually being adopted by designers in professional design practice; our notion is that it is rare. A reason might be that current proposals for procedures and methodologies are only assumptions of, or they interprets wrong, what architects actually need [9].

Petersen et al. [10] reviewed studies regarding the use of thermal and daylight building simulation tools in the early design phase and conducted their own qualitative survey to identify the barriers among Danish architects for using these types of simulation tools in the early design phase. The overall conclusion from the literature review was

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that architects in general are interested in using information from such tools in the early design phase to inform their process, but only if they are conformed to fit their design process. Furthermore, the following main barriers for using building simulation tools in the early design phase were indicated in the qualitative study: 1) engineering performance issues regarding indoor climate is basically considered irrelevant in relation to form-giving in early design phases, 2) a concern that (measurable) engineering performance issues may overrule ("non-measurable") architectural design issues, 3) mindset and workflow mismatch between architects and engineers when designing, 4) a desire to use simulation tools for design but current ones are insufficient and inappropriate, and 5) limited economy allocated to the early design phase (e.g. in competitions) is a barrier to close collaboration between architects and engineers. These barriers are similar to those identified by Kanters et al. [11] who based their study on interviews with 23 architects and with a questionnaire surveys with 350 architects as respondents.

The barriers for the uptake of BPS in the early design stage in professional practice seem well-documented, why next step in research should be focusing on identifying ways to overcome these barriers. Clarke and Hensen [12] share this same position and highlight the need for future research in guidelines on how to integrate the use of BPS tools for decision support into actual design practice. However, according to de Souza [13], recent research methods tend to focus on the barriers rather than solutions. Consequently, we need to formulate new and more solution-oriented research methodologies if we want to overcome these barriers and provide useful guidelines on how to integrate BPS tool into early design practice. In this paper we therefore propose a research framework suitable for investigating the following research objective: *to develop BPS tools conformed to fit common design practice in the early design stage*.

To this end, we first reviewed the research methods and approaches used in existing research concerning the development of building performance simulation for decision support in the early stage of building design (Section 2). This review revealed that some researchers made use of research methods originating from other fields of research, namely design research, social science, software development and innovation research which inspired us to do a more comprehensive review of methods originating from these fields of research as they might hold other methods and approaches relevant to a research framework for investigation of the research objective (Section 3). Based on the reviews described in Sections 2 and 3, we propose a new research framework for pursuing the research objective (Section 4). Finally, we then report on an experience from practical application of the research framework (Section 5).

2. Review of research methods and approaches

To help navigate the search for relevant scientific literature, we first unfolded the research objective by defining a number of topics related to the two main themes in the research objective, namely *design practice* (in the early stage), *BPS development*, as well as topics related to their overlapping theme *BPS integration* (Fig. 1). We then used these themes and topics as keywords in the search for current literature related to the topics. The identified literature was reviewed to identify their (1) research methods, i.e. the specific technique used for collecting research data, and (2) research approaches, i.e. whether any overall research theories were followed when executing research methods.

Table 1 provides an overview of research methods used in studies related to the themes and topics in Fig. 1. The overview makes use of a certain terminology which is explained in the following.

Literature review as method refers to use of background knowledge from the scientific field. Not surprisingly, all studies present a more or less extensive literature review of existing work as a part of their research method; the purpose is mainly to fit their own contribution into the current body of knowledge.

The majority of studies used *prototyping* and/or *case studies* as research methods. In the overview, we distinguish between tool prototyping and workflow prototyping: In *tool prototyping*, the researcher scripts a software application which either connects multiple of existing BPS tools with a flow of data (e.g. Lauridsen and Petersen [30]), builds new simulation algorithms or adds to existing simulation models (e.g. Turan et al. [36], Purup and Petersen [37] and Petersen and Svendsen [2]), or provide a new type of graphical user interface (GUI) (Petersen and Svendsen [2], and Attia et al. [7]). In *workflow prototyping*, the researcher proposes a procedure of steps which integrate the BPS tool into the design process, e.g. a procedure based on optimization in which a loop of simulations is continuously executed while evaluating towards a better design solution (e.g. Lauridsen and Petersen [30], Lin and Gerber [8], and Nikolaidou et al. [33]), or use of parametric variation and sensitivity analysis as input before decision-making (Østergård et al. [31] and Petersen and Svendsen [2]). The high frequency of *prototyping* as method indicates that researchers want to address the lack of appropriate tools which has been identified in several studies. As a consequence, there has been a vast increase in the emergence of new tools over the last few years (Østergaard et al. [21]). However, the new tools often also bring new perspectives on tool integration in design practice; the point of origin for many papers is that the current tools do not match the design practice. To support this point, many refer to or provide a *tool review* of present tools to identify strengths and weakness in the state-of-the-art BPS tools, or to identify common gabs in tool capabilities in which their own tool may add new value (Attia et al. [7], Østergaard et al. [21], Morbitzer [38] and de Wilde [39]). Papers presenting a new BPS tool prototype tend to only briefly describe their research methods and then focus on describing the capabilities of the tool.

We define *Case studies* as applications of research in either a *real* or *hypothetic* building context. In general, case studies are primarily made to exemplify the practical use of a tool or workflow prototype, but also to identify lack of tool application in present design process (de Wilde and Voorden [17] and Struck et al. [18]). The case study from the real world can also be described as a field study that has to deal with the

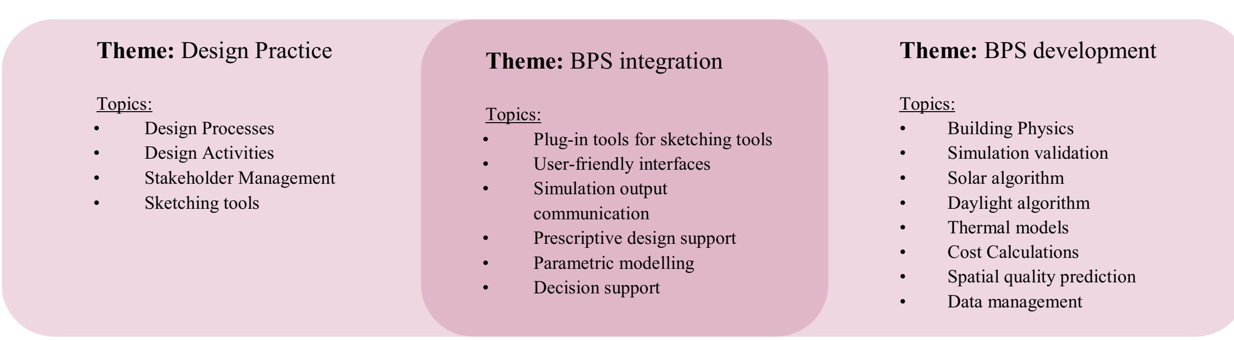

Fig. 1. Topics of the two main themes of the research objective and their overlap.

Table 1
Overview of research methods used in studies concerning building performance simulation in the early stage of building design.

		Literature review	Tool review	Case studies, from real world	Case studies, hypothetical	Self-experience	Interview (un-/semi-structured)	Surveys (structured)	Prototyping, tool	Prototyping, workflow	Diary	Experiments with architectural students	Experiments with engineer students
Journal papers	Augenbroe [14]	X	X										
	de Wilde et al. [15]	X											
	de Wilde et al. [16]	X					X	X					
	de Wilde and Voorden [17]	X			X		X	X		X			
	Struck et al. [18]	X			X		X					X	X
	Petersen and Svendsen [2]	X			X				X	X			
	de Souza [9]	X											
	Attia et al. [7]	X	X		X			X	X	X			
	de Souza [13]	X			X						X	X	
	Gerber and Lin [19]	X			X				X	X		X	
	Kanters et al. [11]	X					X	X					
	Lin and Gerber [8]	X						X	X	X		X	
	Negendahl [20]	X											
	Østergaard et al. [21]	X	X							X			
	Alsaadani and de Souza [22]	X					X	X					
	Alsaadani and de Souza [23]	X						X					
	Gerber et al. [24]	X			X				X	X			

(continued on next page)

Table 1 (*continued*)

		Literature review	Tool review	Case studies, from real world	Case studies, hypothetical	Self-experience	Interview (un-/ semi-structured)	Surveys (structured)	Prototyping, tool	Prototyping, workflow	Diary	Experiments with architectural students	Experiments with engineer students
Conference papers	de Souza and Knight [25]	X								X			
	Attia et al. [26]	X	X					X					
	Weytjens et al. [27]	X					X*		X			X	
	Hemsath [28]	X											
	Dogan and Reinhart [29]	X			X	X				X			
	Lauridsen and Petersen [30]	X			X				X				
	Petersen et al. [10]	X					X						
	Østergård et al. [31]	X		X		X			X				
	Fang and Cho [32]	X			X					X			
	Nikolaidou et al. [33]	X		X						X			
	Schwartz et al. [34]	X			X				X	X			
	Singaraval et al. [35]	X			X				X				
	Turan et al. [36]	X								X		X	
	Purup and Petersen [37]	X							X				
PhD thesis	Morbitzer [38]	X	X	X				X	X	X			
	de Wilde [39]	X	X		X			X	X	X			
	Negendahl [40]	X		X				X	X	X			
	Banke [41]	X		X			X	X	X		X		
	Petersen [6]	X		X			X	X	X	X			X
	Total	35	6	9	10	2	9	13	15	17	2	6	2

* Focus group interview in a session with 10 architects.

"messy" reality and complexity of different approaches among multiple stakeholders in the process, while the hypothetic case study is artificial and tends to exemplify an ideal world with less complexity and typically a more linear process. The relatively high frequency of case studies as a method indicates that much research focus on the practical application of tools in the early stage of design practice. While the use of case studies is highly represented as method in current literature, only very few describe a use of *diary* as a method to keep track of their research activity during the case study. However, not reporting use of diary as a method is not necessarily the same as lacking research recording e.g. in a note book or like.

In *interviews* and *surveys,* users of BPS tools or participants collaborating with users of BPS tool are asked about their opinion regarding usability and relevance of BPS tools to the development of the design. Typically, the interviews or questionnaires are conducted at the end of a case study to evaluate a prototyped tool or workflow (Banke [41], Negendahl [40], and Lin and Gerber [8]). Only few use interview and surveys before developing a prototype (Kanters et al. [11] and Petersen et al. [10]). Some studies base their development on prior knowledge from other studies (Petersen [6], Petersen and Svendsen [2], and Negendahl [40]), while other base their tool development on self-experiences (Dogan and Reinhart [29] and Østergård et al. [31]).

A few studies used tasks for participants in student classes for debugging of prototypes and gain a large amount of feedback on tool usability (Petersen [6] and Gerber and Lin [19]) defined as *experiments with students* in Table 1. Then applied with caution, tendencies in design practice might also be measured and used for statistical purpose as demonstrated by Struck et al. [18].

The literature review revealed that reflections on the applied research approach are rare in scientific papers. Ph.D.-theses on the other hand tend to have more elaborated descriptions of research approaches, e.g. Banke [41] who applied the approach of Schön in his case studies, and Petersen [6] who applied the *hypothesis-deductive* approach [42] along with the "seeding, evolutionary growth, and reseeding" model (SER) by Fischer [43] for testing hypotheses. Many research fields acknowledge that considerations about research approaches need as much attention as the research domain itself. The evident lack of methodological considerations in the current literature may therefore be a reason why the prevailing research approach continues to be self-invented prototypes of tools and workflows even though this approach does not seem to lead to an increased adoption of BPS in the early stages of actual design practice.

An additional outcome of the literature review was that we realized that some studies makes use of research methods originating from other fields of research, namely design research, social science, software development and innovation research. This inspired us to do a more comprehensive review of research methods and approaches used in these research fields and relate them to the objective of this paper (Section 3).

3. Research methods and approaches from related fields

In this section we report on a review of research methods and approaches used in other related fields of research, namely design research, social science, software development and innovation research. These fields have a large and growing body of research. We therefore only provide the reader with a brief overview of research methods and approaches used in these fields by referring to the content of a few but representable publications, and instead focus more on describing how they might be relevant to include in a research framework suitable for pursuing the research objective identified in this paper. An overview of identified methods and approaches found relevant to the objective of this paper is shown in Table 2.

3.1. Design research

Design research emerged as a recognizable research field in the 1960s. Over the years, several methods and approaches for design research[1] have been proposed and developed. An exhaustive review of this topic is considered out of scope of this paper; instead, we refer the reader to recent monographs on the subject such as Laurel [44], Blessings and Chakrabarti [45], Koskinen et al. [46], Hanington and Martin [47] to mention but a few. However, the researcher we in this paper have selected to represent the prevailing notions in the field of design research is Nigel Cross. Nigel Cross has conducted research in design for decades and summarizes in his book "the designerly ways of knowing" [48] the research methods applied by himself and other leading researchers in design research as follows:

- Interviews with outstanding designers — mainly semi-structured
- Observations and case studies in real projects
- Protocol studies (lab experiments) — on a variation from student designers to expert designers.
- Reflection and theorizing from literature and self-experiences

The above listed methods are in fact also used in current research on BPS for the early stage of building design (see Table 1). However, Cross [48] argues that design is a research field of its own; science of nature considers phenomena of nature; social science considers phenomena of human experiences and social relations, while design research considers phenomena of the artificial (the created), the doing, and the making. As a consequence of this, Cross argues that a design *researcher* must also be a *designer* (i.e. not rooted in any of the classic research fields) to be able to research the phenomenon of design. However, in relation to the research objective identified in this paper, the phenomenon to be researched seems to involve issues related to a mix of research fields, why multiple experts are needed or the researcher needs to be educated in multiple fields. This notion can also be derived from the work of de Souza [13] who suggests a research method in which architects (i.e. designer) are educated in building physics (i.e. natural science) and then used in research of BPS for design.

Cross [48] considers design in relation to "*people, processes and products*". To study people and processes in design, Cross writes: "*Personally, I am particularly interested in what the best, expert designers have to say about design, because they may help us to develop insights into what it means to think, not just like any of us, but like a* good *designer*". Following this advice, it seems relevant to include interviews of expert designers in the research of BPS tools development for decision support at the early design stage.

In relation to study of products Cross looks into sketches, mock-ups, models and drawings of designers: "*Pragmatically, the most essential thing that any designer does is to provide, for those who will make a new artefact, a description of what that artefact should be like… The designer's aim, therefore, is the communication of specific design proposal*". Particular the sketch was interesting to Cross because "*…sketches enable designers to handle different levels of abstraction simultaneously*" and this seems to be an important part of what he calls "design thinking". A sketch can be created in a hand drawing by pen, but also in a computer model; integrating BPS to digital sketching might therefore be relevant to the research objective identified in this paper.

In relation to observations in case studies as a method, Cross often references Schön [49] who has studied the tacit knowledge of practitioners, and seeks to articulate this knowledge by '*reflection-in-action*', typically in case studies. Schön's work [49] indicates that knowledge can be investigated by reflective participation in case studies. Though Schön is not directly from the design research field, he is often

[1] Research understood as "a systematic enquiry, the goal of which is knowledge" (Archer 1981) – in this case knowledge about design activities in practice.

Table 2
Summary of research methods and approaches from related fields.

Field of research	Approaches	Methods
Design research	"The designerly way of knowing" [48]	Interviews of expert designers
	"Reflection-in-action" [49]	Study of sketches
		Case study of design projects
		Lab experiments with student designer
		Theorizing on literature
Social science	Heuristic (verifying a hypothesis)	Semi-structured interview
	Phenomenology (keeping an open-mind)	Surveys/questionnaires
	Narratology (analyzing the stories of people)	Observations
	Grounded theory (coding transcriptions)	Diary
Software development	UX design (user experience design)	Interview
	Action research	Statistics
		Personas
		User-scenarios
		Wireframing
		Prototyping
		User-tests
Innovation research	Co-creation	Design game

referenced in design research, e.g. by Volf [50] who uses his approach in her observations in a design company over three years, and Davis [51] that adopts the approach when participating in case studies during his PhD on parametric models in architectural practice. According to Table 1, case studies were frequently represented in BPS research since this method can be used for testing the level of success in BPS integration, but only a few studies described a research approach for securing scientific reflection; use of the research approach of Schön could be a contribution to ensure this.

3.2. Social science

Research methods used in social science, such as semi-structured interview, surveys, case studies, literature review, and diary [52], are also currently used for BPS development (see Table 1). Other research methods from social science which are not identified as being used in the BPS development literature are *focus group interviews* and *video-observations*. All these methods can in general be regarded as research instruments but in social science it is regarded as paramount that the researcher is aware of how these methods are applied in terms of research approach. For example, an interview is not just a dialog between the researcher and the subject; the researcher needs to consider own involvement and theoretical research approach accordingly to the aim and perspectives of the research [52,53]. Hermeneutic and phenomenology are two theoretical research approaches often mentioned in social science literature — approaches which are in contrast to each other in many aspects. In hermeneutic, the researcher has a theory or hypothesis to follow and test, while phenomenology studies a phenomenon without such prejudices. Both approaches have strengths and weaknesses. A pro hermeneutic researcher will claim that the researcher needs solid background knowledge to know what to look for and avoid misunderstandings; otherwise the researcher risk not finding or proving anything, while the pro phenomenological researcher will claim that a researcher with an agenda only finds what the researcher look for, and then risk forcing the research in a certain direction. Though these two approaches to a wide extent are opposite and conflicting, we believe that research for new solutions concerning BPS tools for early design practice could benefit from the use of both approaches as it might be relevant to know what to look for and understand the area of research (hermeneutic), while being open to new perspectives in order to find new science contributions (phenomenology).

Another approach going a step further than the phenomenology is Grounded Theory [54]. The aim of this approach is to build new theories instead of testing old ones, and the theories must be grounded by qualitative research (almost) without any interfering from the researcher. Glaser and Strauss [54] claim that the researcher must be completely sensitive to the research by having no pre-knowledge when conducting the research. In the analysis, the researcher codes the transcriptions from interviews by themes, then sorts the themes into categories and finally develop a theory based on the categories. This analysis technique is very systematic and limits the influence by the researcher. Critics (Heidegger (1962) in Alvesson and Sköldberg [55]) of this approach claim that it is impossible to be completely sensitive to the research; the researcher is usually already some sort of expert, and it is wrong to neglect the motivation and intentions of the researcher. If this is true, then grounded theory may not go so well with research approaches from design research where it is claimed that the researcher should be an expert in design [48]. Furthermore, the coding technic of grounded theory – when analyzing empirical material – has a tendency to cut up stories of the subjects, and the stories may carry important meaning or symbols in relation to the research.

In contrast to Grounded Theory, narratology is another approach which looks into these stories or narratives that subjects tell. In narratology, people explain their reality through stories. These stories are constructed and told many times. By analyzing the structure of the stories, the researcher may find intensions and self-understanding of the subjects. This approach is mainly used in research of politics and linguistic, but could also be used to explain the practice of architects. In relation to practice, one could argue that observing what people do instead of asking them what they do provides a more trustworthy insight. Observation as method for investigating design practice can however be very time-consuming: Volf [50] used three years observing one design group. Furthermore, it can be difficult to guess the intension behind actions without asking. We therefore see a potential in asking architects *what they do* (explained in narratives) and *why they do it*; this could in contrast to time-consuming observations result in a larger sample of different architectural design practices as well as leading to a deeper understanding of the underlying mechanisms of design practice before proposing how to integrate BPS tools.

To navigate between above listed research approaches, Brinkmann and Tanggaard [52] emphasize the importance of being reflective in conduction of qualitative research, and not blindly follow procedures from acknowledged research approaches. They argue that research procedures tend to describe an ideal process, but reality is 'messy' (i.e. anything but ideal) and, consequently, there is a risk that the research does not yield new contributions if the theoretical procedures are strictly followed [52]. The researcher should therefore use own logical sense when navigating through collected research material or data and make reflections regarding the theoretical and methodological setup throughout the research process, and be open to the fact that new insights may raise the necessity of revising the research methodology. This is not the same as ignoring the theoretical background and current state-of-the-art; without this, the researcher is not able to distinguish between or put into perspective new and old research findings. By emphasizing the reflection of the researcher, Brinkmann and Tanggaard [52] argue that a researcher can have a solid pre-knowledge, and at the same time force themselves to have an “open mind” without pre-judging or forcing a result.

There are several other research approaches described in social science literature, e.g. *Social Constructivism*, *Critical Realism* and *Actor-Network-Theory* to mention a few, but we have limited the reporting in this paper to only encompass the previous explained approaches as they were found to be the most relevant approaches for the research objective identified in this paper.

3.3. Software development

In software development, a common research approach mentioned is *Action Research* (AR) [56]. This approach originates from social science, where Lewin [57] describe AR as “…*research which will help the participants*” and defines it as “…*a spiral of steps each which composed of circle of planning, action, and fact-finding about the result of action*”. AR is thus meant to both improve the situation of the subjects, which in Lewin's case is social minority problems in the state of Connecticut, as well as informing the researcher with fact-findings. McKay and Marshall [58] have done a critical review on AR, finding that literature using AR tends to focus less on the process and data-collecting techniques than the context and content. They question conduction of sufficient academic scrutiny and the possible bias of a participating researcher but their main criticism is that users of AR may have a lack of research interest, i.e. tend to ignore or forget the scientific contribution of their research. Therefore, McKay and Marshall [58] re-introduce AR as a dual cycle of two integrated cycles of interest; Interest of *problem solving* and interest of *research*. The first interest initiates with a problem in a context among problem-owners, the latter initiates with a research question, hypothesis or research theme. McKay and Marshall acknowledge the benefit that AR study phenomena in the “real world” instead of a controlled lab environment, despite of the increased risk of interruption by research as participator, lack of replication, and “messy” reality, but they warn researcher on possible pitfalls in conduction of AR. AR have also been used in later design research, e.g. by Davis [51], who describes his research approach was a circle of planning, acting, observing, and reflecting, referencing the book of Kemmis and McTaggert [56]. The benefit of using AR in relation to BPS research is two-fold: First, the AR approach secures a structured procedure which allows incremental research development in a loop of research activities, and secondly, the approach allows user involvement which may improve the uptake of BPS tools in early stage design practice.

Software development often makes use of *prototyping* as a method, which also have been used in current research on BPS for the early stage of building design (see Table 1). By creating a simplified early edition of the software – even with limited functions – the developer can gain valuable feedback from potential users and clients prior to actually developing the software. Prototypes have been used for many years in manufacturing engineering to test in-expensive early editions of products before the expensive mass production. Mass production of software is however not expensive since this is only a matter of file copy and distribution. However, the software industry has realized that early failures in code can become very expensive later, and these failures are often related to misunderstandings or lack of client requirements [59]. Therefore, prototyping can be a useful method to build bridge between clients and developers. This is also one of the reasons defined in a later review of prototyping strategies by Tate [60]: “*the primary reason for prototyping is to buy knowledge and thus reduce uncertainty and increase the likelihood of success of a software project. The knowledge sought may relate to clarification of requirements, feasibility, user acceptance, marketability, system behavior, or critical performance factors*”. Though this knowledge is meant for development of better software, we see how gathering this type of knowledge – e.g. concerning user requirements – can be useful in relation to the research objective identified in this paper as well. It might even be the only possible way to truly describe how a BPS tool should be conformed to fit the early design practice because users rarely know what they need if asked. Maguire [61] describe different types of prototyping in relation to user-centered design of software applied at different stages of the software development: initiated with early paper prototypes (presenting images concerning interfaces); proceeding with software-based prototypes concerning functionality and study of work procedures in the practice.

Another issue in software development that could be relevant to BPS development is the emerging field of *User Experience Design* (*UX Design*) which focuses on enhancing the emotional pleasure of the users when interacting with a software application [62]. Typical methods used in the UX Design is: *user-interviews*, *user-research* based from statistics, sketch of *personas* describing possible user types in details, sketch of *scenarios* and *storyboards* with software application in use to analyze user satisfaction, emotions, pains and gains on specific user-cases, *wire-framing* of software, *prototyping* and *user-tests* [63]. The intention in UX Design is to provide a more holistic user-centered design that not only consider the usability of a tool (by eliminating pains), but also provide a deeper psychological and emotional satisfaction (by creating gains) which maintain the users interest in the application [62]. BPS tools today are mainly developed by simulation experts who represent a quite different persona compared to a typical building designer [9] in relation to emotions, needs and attractions. If the building designer shall consider using BPS tools in the early design stage, the BPS tool developer may benefit from considering the different personas of building designers as well as the personas of the simulation experts such as de Souza and Tucker [64].

All methods and approaches mentioned in this section seems relevant to apply in the development of BPS tools targeting early stage design practice to provide a more user-oriented design of the BPS tools.

3.4. Innovation research

From the field of innovation research, we want to highlight *Co-Creation* as research approach and *Design Game* as research method. Like Action Research (see Section 3.3), Co-Creation involves problem-owners but focuses on the creation and design of new paradigms, products or solutions (e.g. buildings, software interfaces, office layout, medical instruments etc.) rather than explaining problems. In Co-Creation, multiple stakeholders – both problem-owners and others with relevant knowledge – are invited into the research and development in order to get multiple perspectives on the research topic and to motivate possible future users. Clausen et al. [65] names this phenomenon “*staging*” or “*creating an arena*”. Binder et al. [66] describe how “*the co-design activities could be seen as lab experiments*” and generally use the words “*laboratory*” or “*Design:Lab*” to describe Co-Creation as “*a mutual learning space*”.

Design Games are often used as research instrument in the Co-creation, which intend to “*trigger participants'imaginations*” and “*building bridges*” between the multiple knowledge of interdisciplinary participants [67]. Binder et al. [68] furthermore describes Design Games as “*a powerful device to establish a potential new reality in a network*”. The rules of design games are, on the contrary to normal games with absolute binding rules, vague and open for reinterpretation which supports the imagination of the participants [67]. The intension of design games is to support the design process and research, and not on the contrary dictate outcome, which could cause bias in the research. The rules must support participants in building a common language. Vaajakallio et al. [67] defines four categories of Game purposes: (1) for research purpose, (2) for building design competences among participants, (3) for empowering the users and (4) for engaging multiple stakeholders. In terms of the research objective identified in this paper, the first two purposes are particularly important, since the subjects know more about their needs

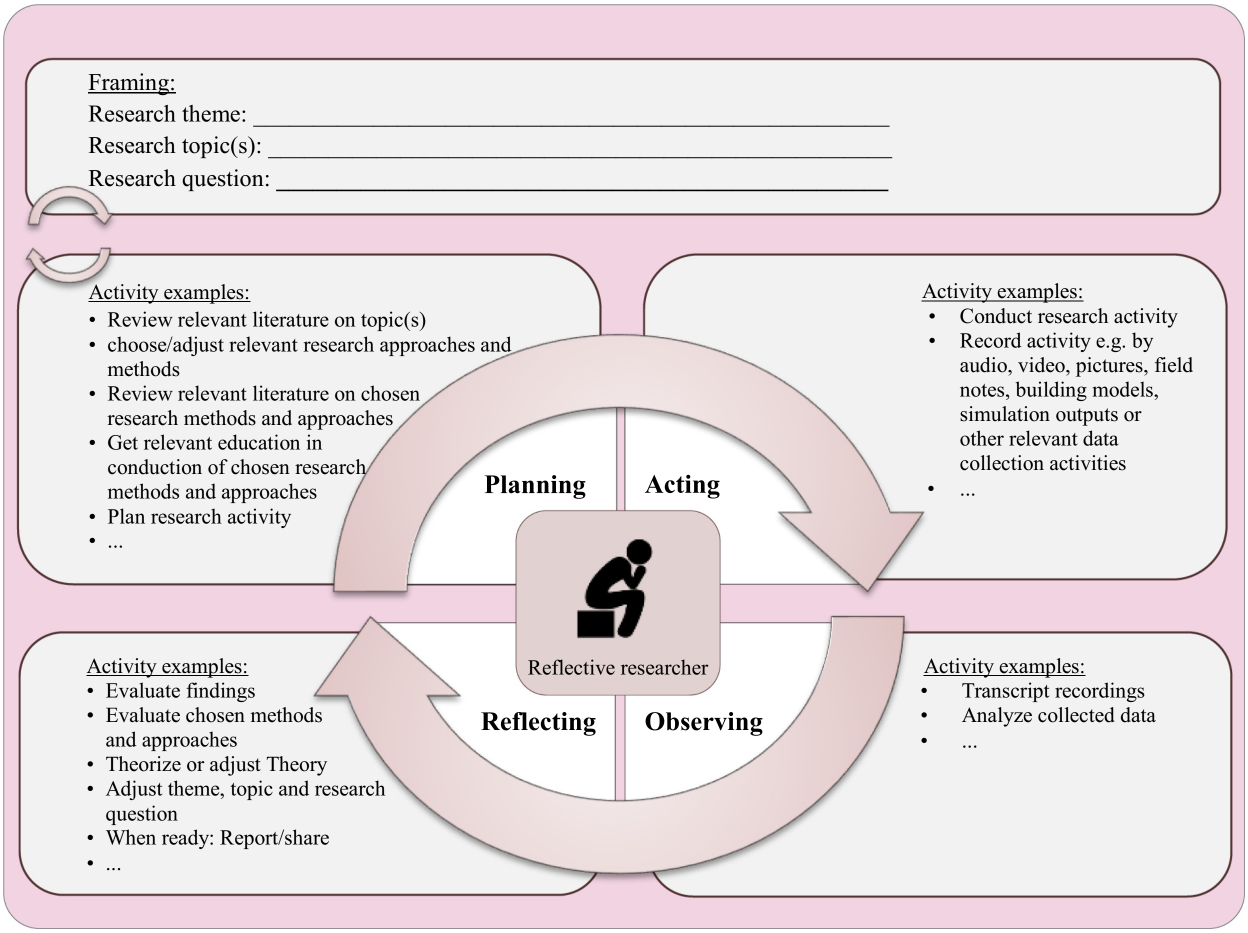

Fig. 2. The proposed research framework for investigation of the research objective consists of a reflective researcher (center) who frames the research by defining a certain research theme, topic(s) and question relevant to the overall research objective (top). Thereafter the reflective researcher follows the workflow known from Action Research (planning, acting, observing and reflecting) when executing a range of research activities related to the chosen research methods and approaches for investigation of the research theme, topic(s) and question.

and their practice than the researcher. Therefore, users need to be involved in the research. Furthermore, if non-experts help designing future paradigms, they need design competences which the design game may reinforce. The two last purposes are, however, not unimportant since they engage future users of BPS tools and their output which is important to the uptake of BPS tools in early stage design practice.

4. Proposed research framework

Based on reviews in Sections 2 and 3, we now propose a new research framework for investigating the overall research objective, namely the development of BPS tools conformed to fit common design practice in the early design stage. The framework is illustrated in Fig. 2 and consists of four main elements:

- the main research approach is the *reflective researcher*, who navigates the research based on continuous reflections on the theories of the research field, the chosen research methods and approaches as well as partial research outcomes [52];
- *framing* which is a rather specific articulation of the research theme, topic and question of interest related to the research objective to be investigated;
- a workflow procedure based on the theory of *action research* that structures research activities (planning, acting, reflecting and observing), secure scientific scrutiny and involve stakeholders [56];
- a range of research activities related to various quantitative as well as qualitative *research methods and approaches* identified in the review Sections 2 and 3 that could be deployed to study the framed research theme, topic and question from multiple perspectives and thereby enable multifaceted conclusions.

The practical workflow of the proposed framework initiate with the *framing* (Fig. 2, top). Thereafter, the researcher starts to do *action research* as a *reflective researcher* (Fig. 2, center). The following sections unfold the four main elements of the framework in the context of the research objective of this paper.

4.1. Reflective researcher as main research approach

The proposed research framework evolves around the *reflective researcher* as the main research approach. A main reason for this is that this approach allows other research approaches such as hermeneutic, phenomenology and narratology to be adopted for investigations of certain research objective, themes or topics within the research field; the reflective researcher as main approach ensures proper navigation between these multiple approaches. Our definition of the *reflective researcher* in the suggested research framework builds on the argumentation of Brinkmann and Tanggaard [52] (see Section 4.2), i.e. the reflective researcher:

- is aware of own involvement by being self-reflective and self-critical during the research process;
- use logical sense to navigate through collected research material and data, as well as when choosing and applying theoretical research

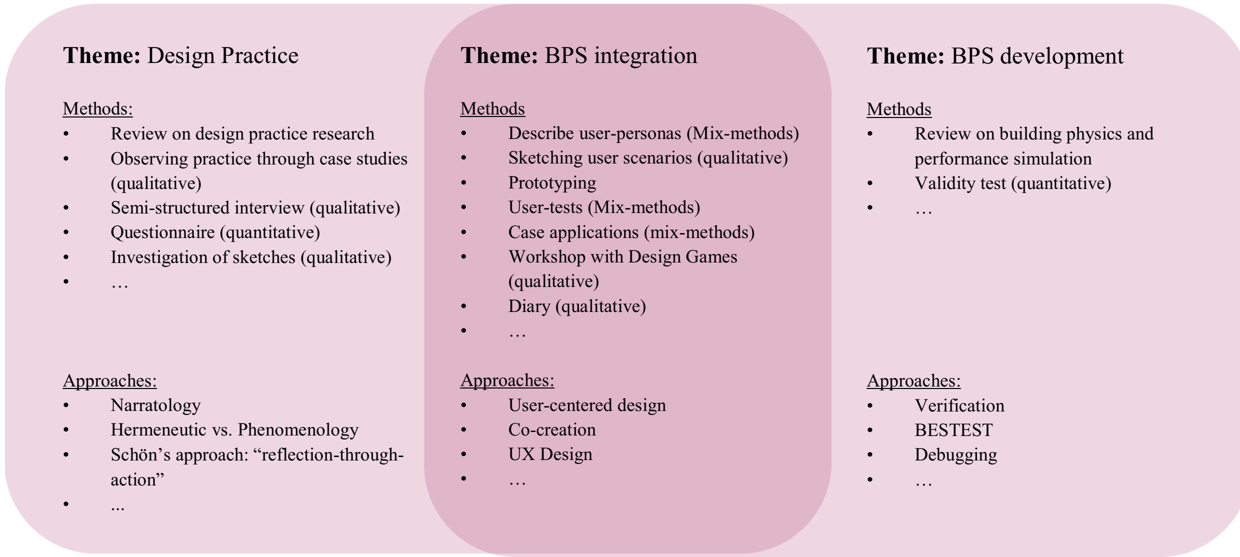

Fig. 3. Research methods and approaches that could be used for investigating the three research themes. Methods can be either qualitative, quantitative or a mix of both.

approaches or methods;
- have a solid pre-knowledge of the research topic, but keeps an open mind for new opportunities or understandings;
- and is transparent about 'what happened' during the research when disseminating the results.

Regarding the latter, we suggest keeping a diary for keeping track of reflection and research activities as a research method to conduct reflective research.

The majority of BPS researchers have a background in engineering or alike, and are therefore schooled in the use of research methods from the quantitative (Newtonian) field of science. Researchers relying on quantitative research have a tradition for minimizing the researcher involvement in collection of research material and data, and a tendency to let collected research material and data "speak for itself". However, the proposed research framework evolving around the reflective researcher results in the possible inclusion and use of qualitative research methods for investigating certain aspects of the research objective. Opposite to the quantitative researcher, the qualitative researcher often needs to be very much involved in the collection of research material and data. It is therefore noted that the use of qualitative methods either requires the involvement of trained qualitative researchers or some form of formal training or practice if it is to be conducted by the Newtonian researchers traditionally involved in the development of BPS tools for the early design stage.

4.2. Framing

The formulation of the research objective of this paper is too broad for any meaningful investigation. We therefore suggest that the use of the framework starts by *framing*, i.e. defining a more specific research theme, topic and question of interest related to the research objective (Fig. 2, top). Researchers may find inspiration for relevant themes and topics listed in Fig. 1, where topics are a subset of themes. The formulation of a research question related to the chosen topic should ask for solutions rather than barriers, and may be helpful to the reflective researcher in planning and navigating the research activities during the next element of the framework (action research). It is noted that the formulation of the framing is not static; the reflective researcher may during the subsequent activities realize that the framing needs adjustment to provide meaningful knowledge. This is considered a legitimate move for a *reflective researcher* [52], and the suggested framework consequently allows for such adjustments.

4.3. Action Research as workflow

The investigation of a framed research question is based on principles from Action Research (AR) as it potentially increases the uptake of research outcome by involving research subjects in the creation of solutions for their own problems, while enables the collection of research material and data for scientific research purposes. The procedure of AR follows a structured loop of planning, acting, observing and reflection (see Fig. 2) to structure research activities and support a high level of scientific scrutiny. Furthermore, AR allows loops featuring various and sometime contradicting research methods, activities or experiments [58]. The intention of this looping is to create a spiral of increased understanding of the research theme or topics as the research-based knowledge accumulates with each loop. Looping also enables triangulation, i.e. validation of research outcome from one independent loop with outcome from other independent loops. Our hypothesis is that the looping features of AR are quite useful in relation to the research objective of this paper. However, as AR almost by definition is conducted among problem owners in their own environment, we suggest that the proposed framework also allows the opportunity for inclusion of experiments in controlled (artificial) environments when deemed relevant by the reflective researcher.

4.4. The use of multiple research methods and approaches

The proposed research framework suggests that the reflective researcher has the option for applying a wide range of qualitative and quantitative research methods and approaches using AR to manage the workflow. The reason for allowing the use of multiple research methods and approaches in the framework is to enable investigations of the same research question using different research methods and approaches with the purpose of strengthening research conclusions through triangulations. Fig. 3 lists a range of suggested research methods and approaches that we find relevant when investigating research questions within the themes (and topics) of the research objective. Regarding the research theme *Design practice*, it seems relevant to include interviews of expert designers in the research, following the advice of Cross [48] (see Section 4.1). However, in terms of the research objective, it is important to navigate the interview towards a discussion of possible solutions rather than barriers. This is why we suggest the use of semi-structured interviews where the interviewer to some extent is able to focus the interview on design practice and wishes for functionality of BPS tools for the early design stage. We furthermore suggest that findings from interviews are "cross-checked" by triangulation with literature and case studies. When using case studies, we suggest the use of "*reflection-through-action*" by Schön [49] as well as the investigation of digital design sketches as suggested by Cross [48].

To develop BPS tools for the early design stage, we suggest that any development is conducted based on outcome of investigations on *Design practice*. That being said, research in the theme *BPS development* should start by doing a review of options for representing building physics, and tool prototypes involving new algorithms should be subjected to validation tests like BESTEST [69] and debugging processes before being released.

To investigate the overlapping theme *BPS integration*, we suggest the use of prototyping as research method as it allows researchers to gain valuable feedback and knowledge on user-experience and practical application of the tool before it is incrementally conformed to fit the design practice. We even regard prototyping to be the most efficient way to identify how a BPS tool should be conformed to fit the design practice because users rarely know what they need if asked (as described in software literature in Section 4.3). We also suggest Co-Creation workshops with use of design game to identify new paradigms for BPS tools, e.g. in relation to user interface and simulation output communication. It is noted that the framework allows for other research methods and approaches than the ones listed to be applied if the reflective researcher finds it relevant.

5. Application example

This section reports on an attempt to apply the proposed research framework in research practice. The intention is to test whether the framework is operational in practice, to provide the reader with a concrete example of how to execute an investigation using the framework, and to test whether the framework is able to generate useful insights regarding the research objective. Fig. 4 provides an overview of this application example in relation to the framing and the chosen research activities in the action research. The following sections provide a narrative description (in step by step) of how the research framework was looped through twice to refine an answer to a framed research question.

5.1. Framing

The proposed research framework was applied for research in the overlapping research theme *BPS integration* (Fig. 1). The research topic was "Parametric modelling" for which we formulated the solution-oriented research question shown in Fig. 4. The question is a product of a literature review on the theme and topic (BPS integration in design practice and parametric modelling) which indicated a potential for applying parametric models combined with BPS tools for decision support in the early design stage (Lauridsen and Petersen [30], Negendahl [40], and Banke [41]). Investigations of applied parametric models and their benefits in a design meeting among multiple stakeholders was however limited and called for further investigation; hence the formulation of the research question.

5.2. First loop

Research activities in the planning phase was to choose relevant research methods and approaches for investigating the research question (including literature review on these research methods and approaches), and, subsequently, various preparations for applying these in the acting phase (see Fig. 4 for details).

The use of the research methods *prototyping* and *case study* in combination with the research approach *testing a hypothesis* was found relevant. Consequently, a solution-oriented hypothesis was formulated: "*A pre-modelled parametric model with much geometrical freedom connected to BPS tools gives useful information for decision-making during a design meeting concerning facade concept development*". The intention was to test this hypothesis using the research methods *prototyping* and *case study participation* (i.e. the researcher participates actively in the case study). A review on existing knowledge on these research methods clarified that the use of the research method *case study participation* called for some more phenomenological research approaches beside the already chosen hermeneutic approach *testing a hypothesis*. Therefore, it was decided to participate in a case study using Schön's approach "reflection-through-action" [49]. The case for the study was a real design competition project featuring a new public primary school. The design team consisted of a group of practicing architects and a BPS engineer (the participating researcher). As a part of the preparation for the acting stage, the building competition program was reviewed and the researcher participated in initial introduction meetings with architects where the next meeting was decided to be about façades. Prior to this meeting, the researcher made a prototype of a parametric model of a classroom in Rhino/Grasshopper, and connected it to the BPS tool ICEbear [37,70] and DIVA-for-Rhino [71]. The parametric freedom of the prototype was room dimensions, facade orientation, window dimensions, number of windows, window placement in the facade, window reveal, overhang dimensions, side fin dimensions, window frames and skylight dimensions and orientation. The geometric potential of the model is depicted in Fig. 5.

The first activity in the acting phase was to attend the planned façade meeting with the architects. At this meeting the architects presented their ideas for a facade concept using a reference picture (Fig. 6). Further discussions revealed that the desired parametric freedom of the reference picture did not match those in the parametric model prepared during the planning phase. The development of ideas on the workshop therefore continued using paper and pencil supported by an argumentative process based on self-experience and intuition. On the initiative of the participating researcher, conceptual variations of shading systems were developed for later BPS and performance evaluation. It was important to the architects that a shading concept would also have a functional aspect i.e. work as a sitting area (Fig. 7).

Activities in the observing phase was analysis of collected evidence from the acting phase (field notes, design log, hand drawn sketches and building models) with respect to the hypothesis formulated in the planning phase. From data it was evident that the parametric freedom of the model prepared in the planning phase was irrelevant to the design team as it did not fit the parametric freedom of the reference picture presented by the architects. As such, the hypothesis could not be supported by data; the pre-modelled parametric model gave no useful information and had no influence on decision making at the meeting. The observation phase in the first loop of the research framework rejected the hypothesis formulated in the planning phase.

The final step of action research is reflecting, and here the following reflections were noted: 1) The pre-defined model could become even more generic, 2) a relevant model could have been pre-modelled if the researcher had gotten the reference picture in advance, and 3) a library of parametric models that covers a wide range of known façade concepts could be the alternative to a single very generic model.

Additional realizations during the reflection phase – observed by keeping an open mind according to Schön [49] – was that this specific group of architects used reference pictures as inspiration, and to establish a common agreed-upon direction of the design. Furthermore, the experience of the researcher participating in the meeting was that the irrelevance of the pre-defined BPS model made the design process quite different than expected; this realization is aligned with the research of de Souza [9] who conclude that BPS integrators have a tendency interpret wrong, what architects actually need. The conclusion from the reflections was that data from this first loop in the research framework was insufficient to make a definite rejection of the

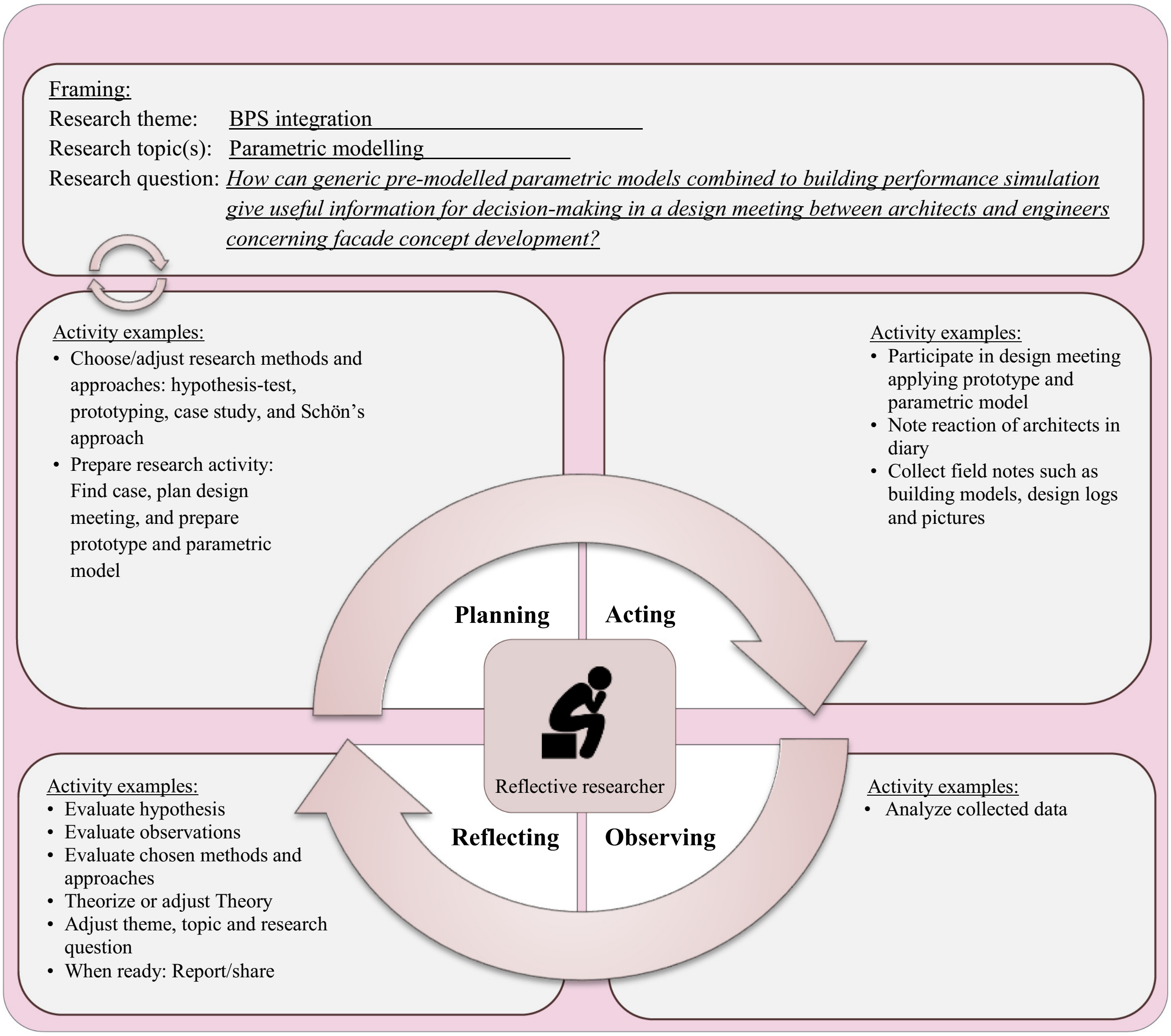

Fig. 4. Overview of the chosen research framing and research activities for the application example.

hypothesis or to answer the research question. It was therefore decided to test the hypothesis again by going through a second loop in the research framework — bearing in mind the experiences from the first loop.

5.3. Second loop

Prior to the next meeting with the architects, the researcher used 3 h to prepare a new parametric model (Fig. 8) accommodating the principle of modular facade system presented by architects at first meeting (Fig. 6), including the parametric freedom to shape the shading concepts developed at the first meeting (Fig. 7), and connected it to the ICEbear and DIVA simulation tools. The experience from the first meeting (see Section 5.2) was that discussions of design alternatives in this design team happened through rapid evaluation of hand sketches. In an attempt to ensure BPS-based decision making, the researcher therefore executed simulations of the five shading concepts for four orientations (north, south, east and west) – a total of 20 simulations – and documented them on paper in a design log (Fig. 9). This design log and the pre-defined parametric model was brought to the next facade meeting with the architects.

In the acting phase, the design log prepared in the planning phase was presented in print (Fig. 9) but the pre-defined parametric model was not used actively at the meeting. The design process at this meeting was similar to the first meeting; paper and pencil supported by an argumentative process based on self-experience and intuition. During this process the researcher used the design log actively to assess arguments with respect to energy, thermal, and daylight performance. The final design ended up having three different facade types (Fig. 10): north and east facing facades had no shading concept, facades facing west had side fins, and south facing facades had deep window reveals and a light shelf.

In the observation phase, it was noticed that the architects in an unspoken way seemed to be uninterested in interacting with the printed design log, let alone the results of the pre-defined parametric model. However, they were quite willing to receive oral information about the outcome of the parametric BPS from the present researcher as input to their additional design considerations.

Reflecting upon the observations, the reason for the unspoken lack of interest in the BPS results and parametric model can only be hypothesized by the researcher since it most likely would be counterproductive to the teamwork if the researcher asked why the architects seemed uninterested in engaging with the printed design log: 1) the architects did not understand the graphics of the simulation output presented in the design log, or 2) the architects preferred an oral discussion using the researcher as a guide to the design log content. Based

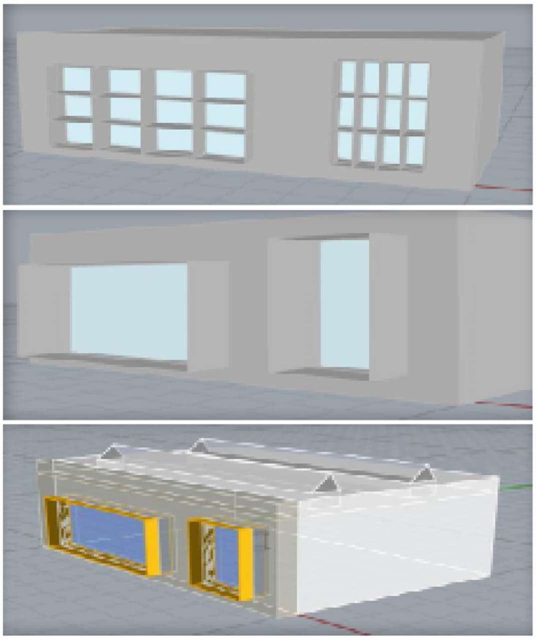

Fig. 5. Three geometric settings of the generic variations made with the parametric model.

Fig. 6. Reference picture presented at the first facade meeting with architects.

on experiences from the second loop, the relevance of the hypothesis seems somewhat strengthened compared to the outcome of the first loop. The pre-modelled parametric model connected to BPS tools was not used actively during the meeting but the simulation outcome of the conceptual variations generated prior to the meeting in the planning phase did help the researcher to orally inform and affect the decision-making during the meeting.

5.4. Reflecting on the application example

As described in the application example, the researcher formally had to reject the hypothesis concerning the research question after the first loop, but analysis of data suggested that the hypothesis still was relevant to investigate if suggestions for adjustments to the proposed solution were implemented. The data from the second loop demonstrated that the implemented adjustments revitalized the relevance of the hypothesis. The application example therefore illustrates the necessity to loop through the research framework multiple times to gain a robust test of a hypothesis. Furthermore, it seems to be a trait that every loop through the proposed research framework has the potential to reveal new aspects and ideas that could be relevant to investigate using the proposed research framework. For example, the loops in this case study revealed a need for a more user-centered approach to the development of BPS output communication and, consequently, the formulation of two new hypotheses. These hypotheses could be investigated using the proposed framework. In the framing of the research, the theme for both hypotheses would be 'BPS integration' and the topic would be 'Simulation output communication' (see Fig. 1). From here on, many research questions could be formulated to investigate the hypotheses. A research question that encompasses them both could be: How should simulation output be visualized to facilitate dialog between disparate participants in the design team? Furthermore, the use of reference pictures as per the first facade meeting gave rise to the idea that a library with multiple parametric models based on reference pictures could be useful to the design team.

6. Discussion

The proposed framework is a formalized research approach intended for investigating the three identified themes of the research objective, namely *Design practice*, *BPS integration*, and *BPS development*. Interestingly, the part of the framework that relies on action research has similarities to formal descriptions of one of the research themes: *Design practice*. The most obvious similarities are found in the descriptions of systematic design methods – the so-called first generation design methods [72] – where researchers view design as a goal-oriented problem-solving activity that is conducted in an iterative manner (Archer [73], Asimov [74], Jones [75]). This view is also the backbone in more recent literature such as the product design strategy "Exploration-Generation-Evaluation-Communication" by Cross [76] and the "Function-Behavior-Structure" ontology by Gero [77]. Furthermore, many of the proposed research methods that can be employed in the research framework (Fig. 3) has been used many times over in current design research literature. It is also acknowledged that some researchers that currently develop BPS for the early stages of building design may recognize elements of their own research practice in this proposed framework and its application example. After all, the proposed research framework to a wide extent builds on methods and approaches which

Fig. 7. Hand drawn sketches of shading concepts from first facade meeting to be tested with BPS afterwards.

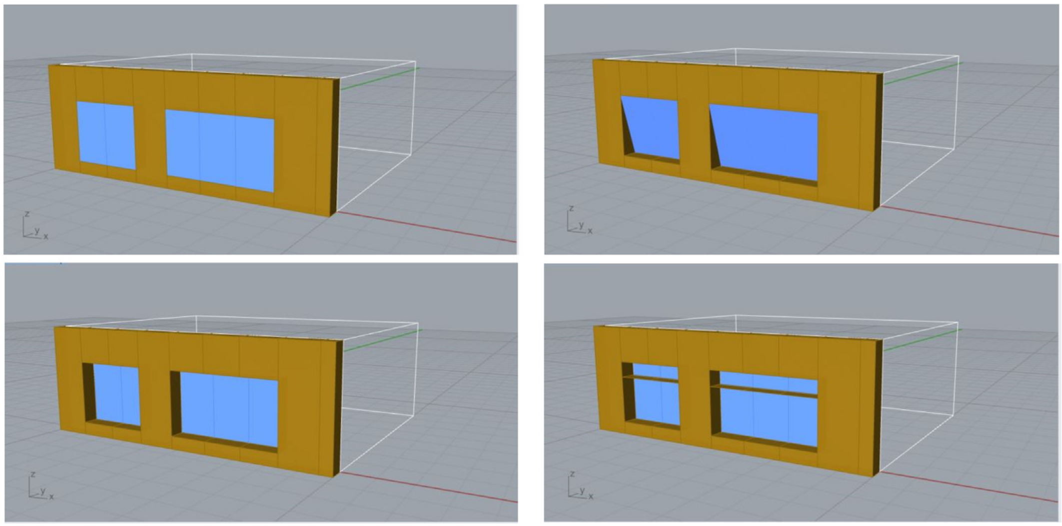

Fig. 8. Screen shots of few variations made with the second parametric model.

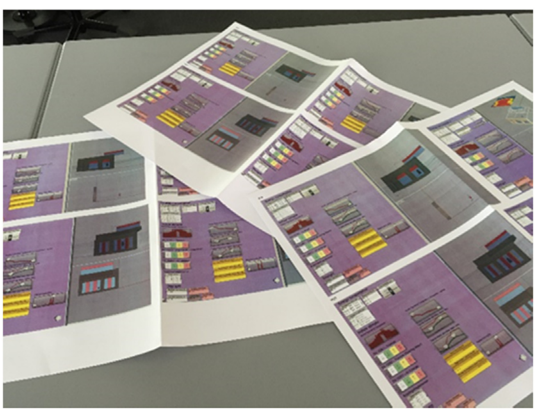

Fig. 9. Parts of the design log with BPS results of the 20 design alternatives, presented at second facade meeting.

already seem to be applied in the field. As such, the proposed research framework is – to a great extent – merely an attempt to offer a generic system to help these researchers to structure, conduct, and document research activities in a systematic manner. What the proposed framework suggests to this specific research community is that research activities must involve interactions with *design practice*, and that the execution of these activities is done *iteratively* as a *reflective researcher*. That being said, the framework could also be useful to other research communities interested in a more practice-oriented development of aspects that should be addressed in the early design phase.

Suggesting the *reflective researcher* as the main research approach does not come without the immediate thought that this approach could be prone to personal biases. However, reflexivity is largely practiced in qualitative research for many legitimate reasons [78]. According to the definition, a reflective researcher – among other things – ensures an ethical conduction of research activities, and does not merely report research findings but also to question and explain how those findings are constructed. To avoid misunderstandings of what it means to be a reflective researcher, it is therefore recommended that researchers who wants to use the proposed framework gets familiar with the definition of a reflective researcher prior to the use of the framework.

The application example reported in this paper is an attempt to illustrate the usefulness of the proposed method by disseminating how the framework performed in actual research practice. Besides useful, i.e. the quality of having (more or less) practical utility, the proposed framework should also be considered usable, i.e. "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [79]. The researcher conducting the research in the application example (who also was the first author of this paper) considered the framework to be useful as well as usable; however, further research is needed to investigate whether the framework is considered to be useful and usable to other researchers. This could e.g. be done by involving other researchers in the execution of new application examples and have them evaluate its usefulness and ease of use, or conduct interviews/workshops with other researchers about the usefulness and ease of use of the proposed framework. The usefulness and ease of use among participants could in both investigations be quantified using the Technology Acceptance Model (TAM) by Davis [80], the USE questionnaire by Lund [81], or a similar scheme.

7. Conclusion

Barriers for the uptake of BPS in the early design stage in professional practice seem well-documented in existing literature, and future research should therefore focus on identifying solutions to overcome these barriers. But if we want to identify solutions, we need to define appropriate research methodologies for investigating the 'phenomenon of solutions' rather than the 'phenomenon of barriers'. In this paper we have therefore proposed a research framework fit for research-based development of BPS tools conformed to fit common design practice in the early design stage. The proposed research framework is based on a review of methods currently used in research of BPS for early stage design support, as well as a discussion of the relevance of approaches and methods from related research fields such as design research, social science, software development, and innovation research.

The paper also reports on a step-by-step application of the proposed framework to test the framework in practice. The test demonstrated that the framework was a helpful tool for systematic navigation and documentation of research activities and collection of data to seek answers to a research question concerning the development of BPS tools conformed to fit common design practice. Furthermore, the test also demonstrated that the iterative nature of the framework helps researchers to continuously increase their knowledge and understanding of the underlying mechanisms of the design practice in early design stage. The framework can therefore enable researchers to continuously improve and test their ideas and suggestions on how to make BPS tools that are conformed to fit common design practice in the early design stage.

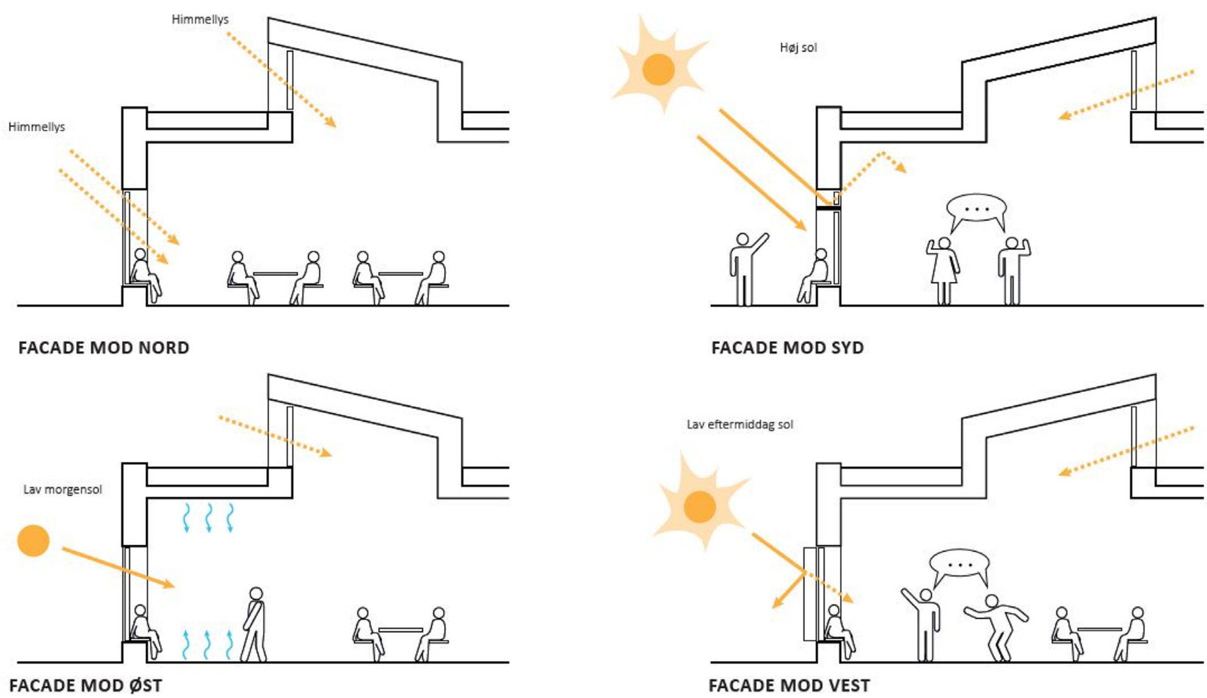

Fig. 10. Sectional drawings of the solar shading concepts of the final design proposal (Illustration: Arkitema).

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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