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REQUIREMENTS MANAGEMENT FOR THE DESIGN OF ENERGY EFFICIENT BUILDINGS

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SUMMARY: *Buildings are designed to fulfil the multiple and, often, contradictory requirements of users, clients and society. Energy aspects are often not considered before the detailed design phase and a systematic way of analysing the energy performance of solutions throughout the design phase is lacking. A suggested framework, based on engineering design theories of requirements management, was applied to a case study of the design of an energy-efficient building in a real construction project. The case study provided qualitative insights into how the proposed framework can contribute to a more structured requirements management of a construction project with a focus on the energy-efficient design of buildings. It can be seen that the proposed framework for requirements management of energy performance provides a structure for designers to consider and apply energy performance criteria in the early design stages and visualize the consequences of alternative design solutions for clients, engineers, contractors and suppliers. The use of a requirements structure enables the transparency of different design alternatives against the established functional requirements of energy performance for the stakeholders in the design process. The use of BIM to support the proposed requirements framework needs to be studied further and connected to national and international construction classification schemas and ontology frameworks.*

KEYWORDS: *Requirement management, Axiomatic design theory, Energy performance, Stage-based design process*

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1. INTRODUCTION

Buildings are designed and constructed to fulfil the demands of users, clients and society. Many of these demands are expressed as functional requirements through building codes, standards and local regulations. The management of the many requirements throughout the design suffers from a lack of transparency which can later lead to solutions in the design process that do not meet the original requirements (Kiviniemi et al. 2005; Haymaker and Fischer 2008; Jallow et al. 2008). This results in design iterations and rework, resulting in low efficiency (Apleberger et al. 2007; Ye et al. 2009). Also, the operational islands between the many design disciplines cause ineffective coordination, figure 1, which can affect the fulfilment of the multiple and often contradictory requirements (Mattar 1983), which in turn can affect the life cycle performance of buildings (Schade et al. 2011). Proper requirements management in this context can reduce the number of design iterations and the amount of rework by providing better integration of the different teams in the design development environment (Gosling and Naim 2009).

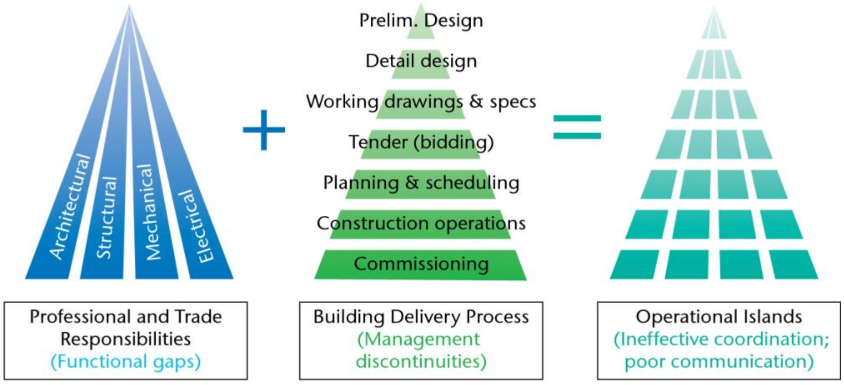

FIG 1 Operational islands from WBCSD (2008), after Mattar (1983)

Many aspects of a building's performance depend on decisions taken early in the design process (Schluter and Thesseling 2009). Space heat consumption of a building can be reduced by up to 80% if orientation, building shape, insulation and ventilation are optimized in the design process (Feist et al. 2005; Smeds and Wall 2007). Energy requirements should be considered for the entire building in the conceptual design phase and then refined throughout the design of spaces, MEP systems and components (COBIM 2012). However, energy aspects are often not considered before the detailed design phase (Schluter and Thesseling 2009), when only minor changes to the design are possible.

When designing sustainable buildings, where tendering and refinement of the product is made through a network of decisions and value processing, there are opportunities to increase design quality (Magent et al. 2009) by focusing on the integration of systems into daily engineering work. A better management of the functional requirements related to the energy consumption of the building can increase the transparency and provide better integration and opportunities for optimizing the energy performance of a building across disciplines in the design process. Schweber and Leiringer (2012) also concluded that "there is a need for research that examines the processes, understandings, and motivations which produce observed patterns and systems for energy and buildings".

The purpose of this paper is to explore a framework for requirements management in the design of buildings that enables traceability across disciplines. A conceptual framework is presented based on Suh's (2001) theories of axiomatic design and requirements-driven product modelling by Malmqvist (2001) in the field of engineering design. The framework is then adapted to a stage-based design process of energy performance as presented by COBIM (2012).

2. THEORETICAL FRAMEWORK

2.1 Theory of Axiomatic Design

The theory of axiomatic design is a systematic method for the design transformation between the customer, the functional, physical and production domains (Suh 2001). The transformations between two domains, such as the functional and physical domains, represent the design task to interpret and translate functional requirements (FRs) into design parameters (DPs), from the most generic and top-level requirement to more detailed requirement levels using zigzag decomposition cycles, see Fig. 2.

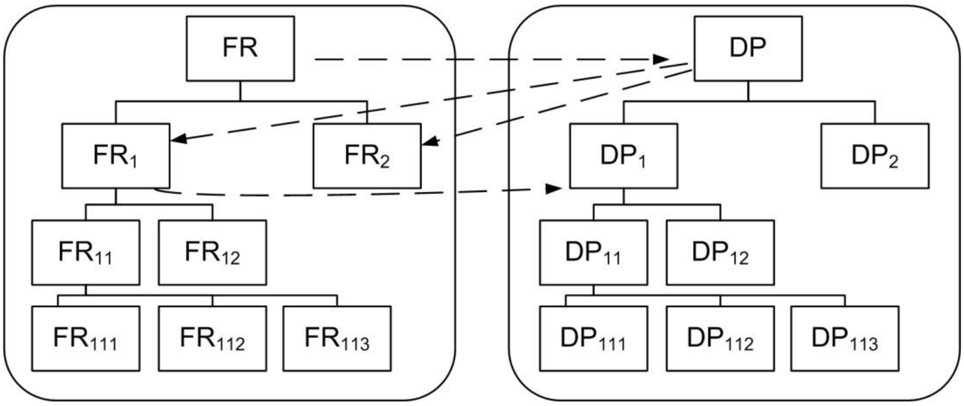

FIG 2 Zigzag decomposition in Axiomatic Design (Suh 2001)

Zigzagging is one of three basic concepts in axiomatic design where the other two axioms are:

1. The independence axiom: Maintain the independence of the functional requirements (FRs).
2. The information axiom: Minimize the information content of the design. Reduce information for the best design solution without affecting the independency of FRs.
   (Suh 2001)

The coupling between FR and DP is defined mathematically as $\{FR\} = [A]\ \{DP\}$ where A is the design matrix. A diagonal (uncoupled) or a triangular (decoupled) matrix fulfils the independence axiom. However, even though this can be hard to accomplish, design solutions with as few off-diagonal elements as possible should be the aim (Suh 2001).

If two solutions have similar coupling matrices, the second axiom states that the best alternative is the solution with less information. Boundary conditions and system constraints are denoted by Cs and restrict the design space. Decisions taken from higher levels stages act as constraints at lower levels (Suh 2001).

The transformations between the domains are normally carried out by different actors with specific product views, Fig 3. In the context of construction, the *architectural view* describes the transformation from customer attributes (CAs) within the customer domain to functional requirements (FRs) within the functional domain. The *engineering view(s)* describes the transformation from functional requirements (FRs) to design parameters (DPs) in the physical domain and the *production view* describes the transformation work from design parameters (DPs) to production variables (PVs) in the process domain. Constraints (Cs) are limitations of downstream activities that have to be considered in upstream transformations, Fig. 3. These constraints can arise as a result of the standardization of components, processes or organizational conditions. Constraints can also describe regulations used at the site or conditions for transportation (Jensen et al. 2012).

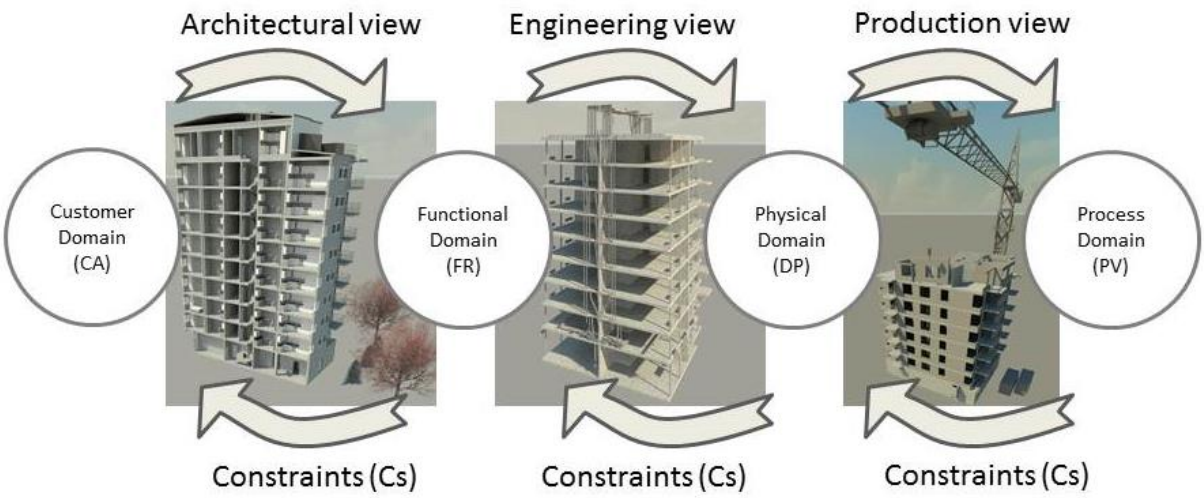

FIG 3 Axiomatic design domains and transformation of the design vectors (CA ⇨ FR ⇨ DP ⇨ PV) from different product views adapted after Suh (2001) and Jensen et al. (2012)

2.2 Requirements Management

According to Fiksel and Dunkle (1993), managing requirements is the knowledge of how to create, maintain and test requirements throughout a product life cycle. Methods of requirements management are categorized according to *eliciting*, *modelling*, *analyzing*, *communicating*, *agreeing* and *evolving* requirements for the system (Nuseibeh and Easterbrook 2000). The requirement management model by Malmqvist (2001) describes the transformation process as a synthesis of required properties for *product definition models* (described as the technical components of the product) and *life cycle system models* (described as production and supply chain systems), Fig. 4. *Property* models describe the properties of the product definition models, which are used to evaluate the performance of the design against initial requirements.

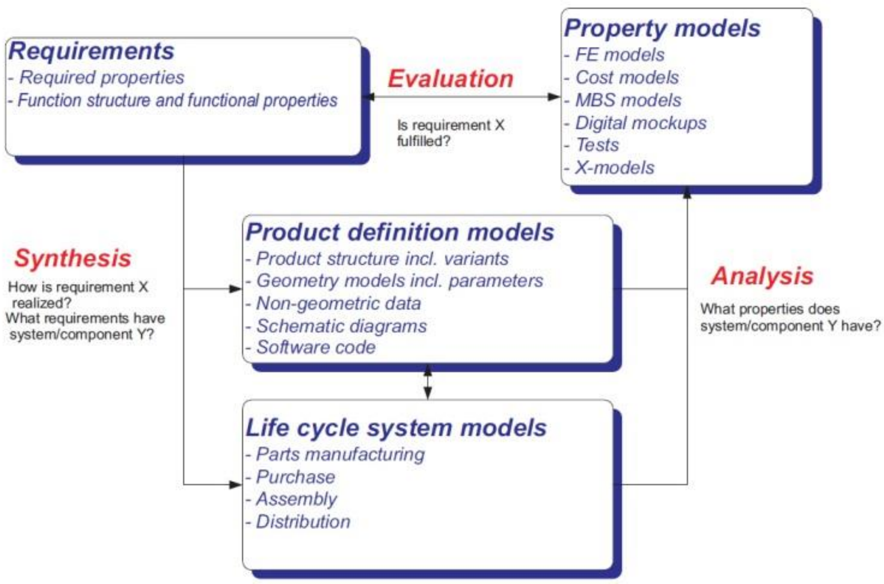

FIG 4 Requirements-driven integrated product and process model (Malmqvist 2001)

It is important to evaluate both measurable quantitative properties as well as properties that are related to qualitative stakeholder values and the functional structure of the design (Suh 2001; Malmqvist 2001).

Requirements in the construction industry are often expressed in terms of *What* is required and *Why* it is required from stakeholders such as clients and users. Design solutions express *how* these requirements should be met by the supplier side (Ye et al. 2009). However, very few research projects have focused on the gap between *what* and *why* and *how* these requirements are fulfilled by the architecture, engineering and construction industry. Kiviniemi (2005) researched how *Requirement Hierarchies* can be managed by *Building Product Models* and proposed the use of space and component objects as carriers of requirements. The transparency between requirements and solutions is another important area to consider in how to reach usability and sustainability from a life cycle perspective (INPRO-D14A 2009).

2.3 Progression in construction design

Engineering design delivers drawings, models, documents and information based on national, regional and client/customer requirements for the planning of work and supply of material to the production system. Two types of strategies can be recognized for the design work: *Point-based design* and *Set-based design*. *Point-based design* narrows down the number of product solutions in the early stages to one preferred alternative for further development. In *Set-based design,* a number of alternative design solutions are kept open to avoid iteration in the design process and to make expensive design commitments as late as possible (Choo et al. 2004). As the design progresses, the number of solutions are slowly reduced. The set-based design strategy requires more design resources and frequent meetings, especially in the early design phase. However, an early agreement on product functionality can lead to faster downstream decisions as the design progresses (Liker et al. 1996).

The use of evaluation, optimization and negotiation are examples of methods that concretize solutions in an iterative design process (Wynn et al. 2007). A concurrent engineering process can reduce lead times in the design (Prasad 1996), but the reviews necessary to ensure the quality of the design can increase the number of iterations and hence the time and cost for that design (Le et al. 2012).

2.4 Design for energy performance

Reducing the use of energy during the operation of a building is one of the most important design factors in construction projects, (Ye et al. 2009). Client requirements and local regulations regarding more energy efficient and sustainable buildings put higher demands on the design process (Malmqvist et al. 2011). So far, most energy research has been focused on methods and tools in evaluation of engineering quantitative data (Attia et al. 2012), while research on the design process for energy efficient building only represent a minor part of the field (Schweber and Leiringer 2012).

The structure of functional requirements in construction design can be decomposed from primary requirements, such as the *energy efficiency of a building*, to lower-level requirements describing measurable criteria, such as low air leakage ≤ 0.6 l/sm^2, that can be controlled using property models of the design solution (Kamara et al. 1999). It is important to include decisions that are critical for energy performance, such as the shape of the building, early in the design process (Bazjanac 2008). Therefore, several frameworks related to the design of energy performance have been proposed.

Schade et al. (2011) introduced a decision-making framework in a performance-based design process. The framework is applicable in a stage-gated design process where objective and subjective performances of design alternatives are evaluated at each gate stage. That piece of research studied an office property in Finland with the focus on the early design stages and energy performance to demonstrate the framework (Schade et al. 2011). In the common BIM Requirement defined by BuildingSMART Finland, an eight stage process for indoor climate and energy analysis is proposed from conceptual design to maintenance (COBIM 2012). Cavique and

Gonçalves-Coelho (2009) proposed a requirement structure using axiomatic design theory to reduce energy consumption in HVAC systems. The energy requirements were divided into five categories, based on the regulations in five countries in the south of Europe.

3. METHOD

The presented case study is part of a research project investigating the design management of building systems for housing. *First* a literature review regarding energy requirements, especially in the early phases of the design in construction projects was conducted. Engineering design, energy design, requirements management and design processes in construction was the base for the literature review.

Secondly a single case study was conducted to gain qualitative insights and understanding on how functional requirements are managed through design within the specific context of energy (Yin 2003). The design of a multi-dwelling house project with approximately 1500 m^2 floor area, situated in the Gothenburg region, by one of the largest contractors in Scandinavia was selected as the case study. The building system for the project is based on prefabricated concrete elements for walls, balconies, structural columns, slab floors and stairs using standard company shapes and components. The requirements of energy use in the project were essentially lower than the level prescribed by the Swedish building code. Design activities were observed in project meetings and design reviews during 2010 and 2011 with focus on the design of the energy performance. Predefined stages with gates were practiced throughout the design process. The stage-based analysis for energy performance mapped well to the proposed COBIM stages where IDA Indoor Climate and Energy (IDA ICE) software was used to analyze the energy performance of the proposed design alternatives in all three stages of the design

Thirdly, a requirements management framework was developed and proposed (detailed described in section 4).

After defining the framework, interviews with questions were formulated in four themes: process stages, requirements, energy analyses, process involvement. The first round was in-depth interviews had questions about operational work to the themes with design project managers, structural engineers and energy engineers from the house building project. Based on the result from observation made at the design reviews, semi-structured interviews were formulated with open-ended question to collect missing data and to get an overall picture of the building project. Interviews was conducted with the project manager, the design project manager, two structural engineers and the energy engineer responsible for the design of the energy performance after the building project where finished.

Finally, the proposed requirements management framework was used as a template in the analysis of the engineering work in the case study. To secure validity between interviews with project managers and engineers, the project log and related design documentation were chosen for the analysed according to all respondents. The framework was not used in the working process in the building project at the case study company but communicated afterwards to respondents and involved persons.

4. A REQUIREMENTS MANAGEMENT FRAMEWORK FOR CONSTRUCTION

The specification of design solutions according to functional requirements (FRs) is already realized in the Swedish regulation, BBR 19 (2011:26). As well as the national regulations, the client's use of the building is now part of the list of FRs. As the design process progresses from higher conceptual levels to the more detailed design of parts and components, the functional requirements also become more detailed (Suh 2001; Nuseibeh and Easterbrook 2001).

A set-based design strategy is recommended to explore multiple options, especially in the early stages when the majority of the decisions taken influence the final costs (Romm 1994). The use of virtual design methods and BIM tools are proposed to manage the design process in the search for design parameters that fulfil the requirements (Haymaker and Fischer 2008; Eastman 2008). In the case of the customization of standardized building systems, the design space is more limited. Some design parameters are already defined and act as constraints (Cs) in the design process (middle field in Fig 5), whilst other parameters can be adapted to customer requirements within fixed intervals. Parametric design of BIM objects can be used here to automatically support the engineering configuration of alternatives (Jensen et al. 2012).

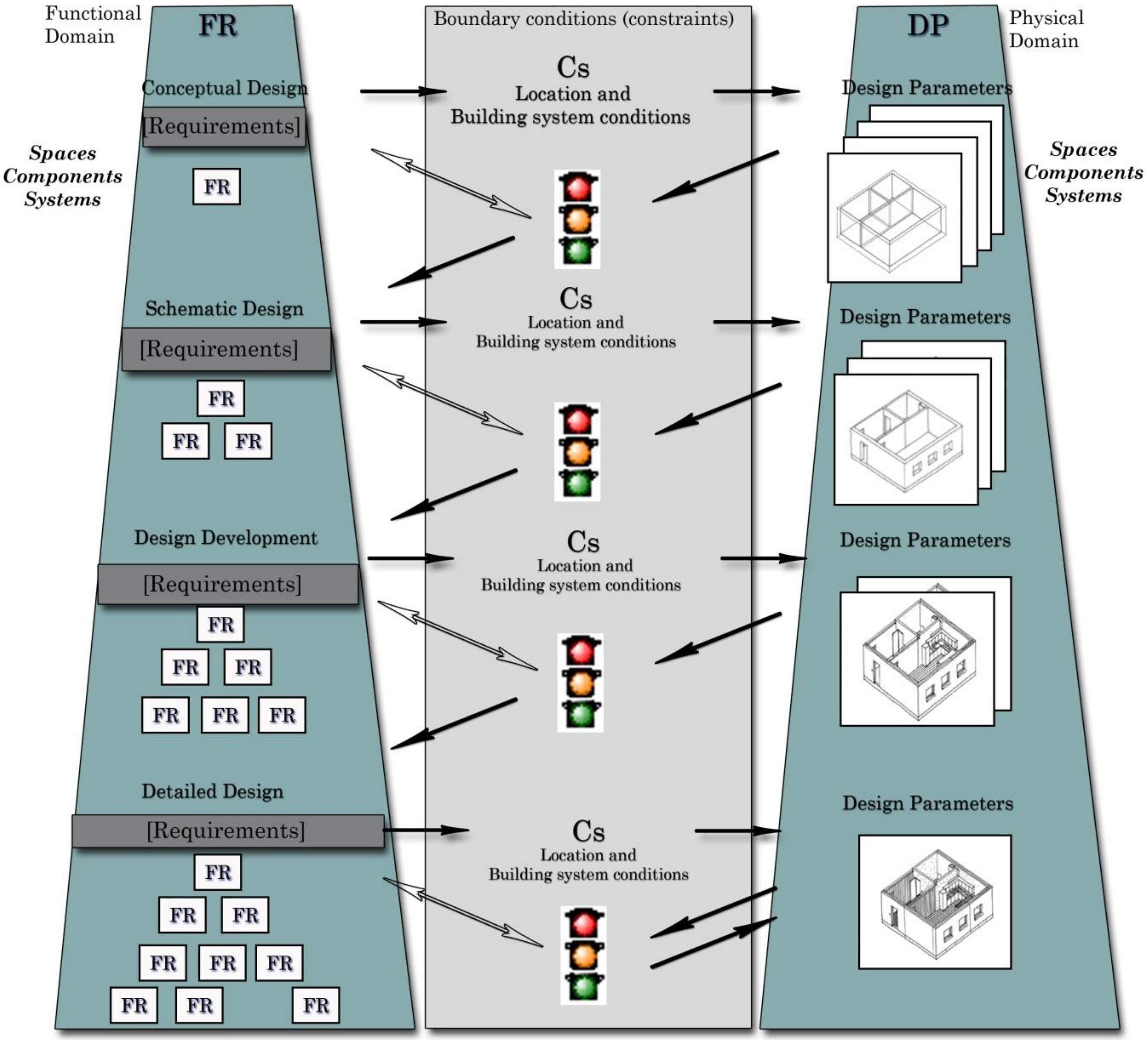

FIG 5 Proposed requirements management model

The detailing of the product is proposed to be defined in a stage-gated design process, Fig. 5, where the zigzag decomposition of FR and DP levels occurs according to the theory of axiomatic design (Suh 2001). Evaluation of design solutions from higher levels leads to new requirements at the lower levels. The use of space objects as information containers for the functional requirements can support the customer view without limiting product solutions in the early design stages (Kiviniemi et al. 2005). In later stages, components and systems can carry information regarding decomposed functional requirements at lower levels. Some BIM tools have the functionality to manage spaces, components and systems but need structures to manage the transition between functional requirements and design parameters and the relationships to building system constraints. The axioms of independency of FRs and information minimization in the proposed solutions can be used as strategies both in the design and evaluation process at each stage to secure the functionality of the product. The entire management of the design process should be based on value-adding iterations and information processing between involved actors.

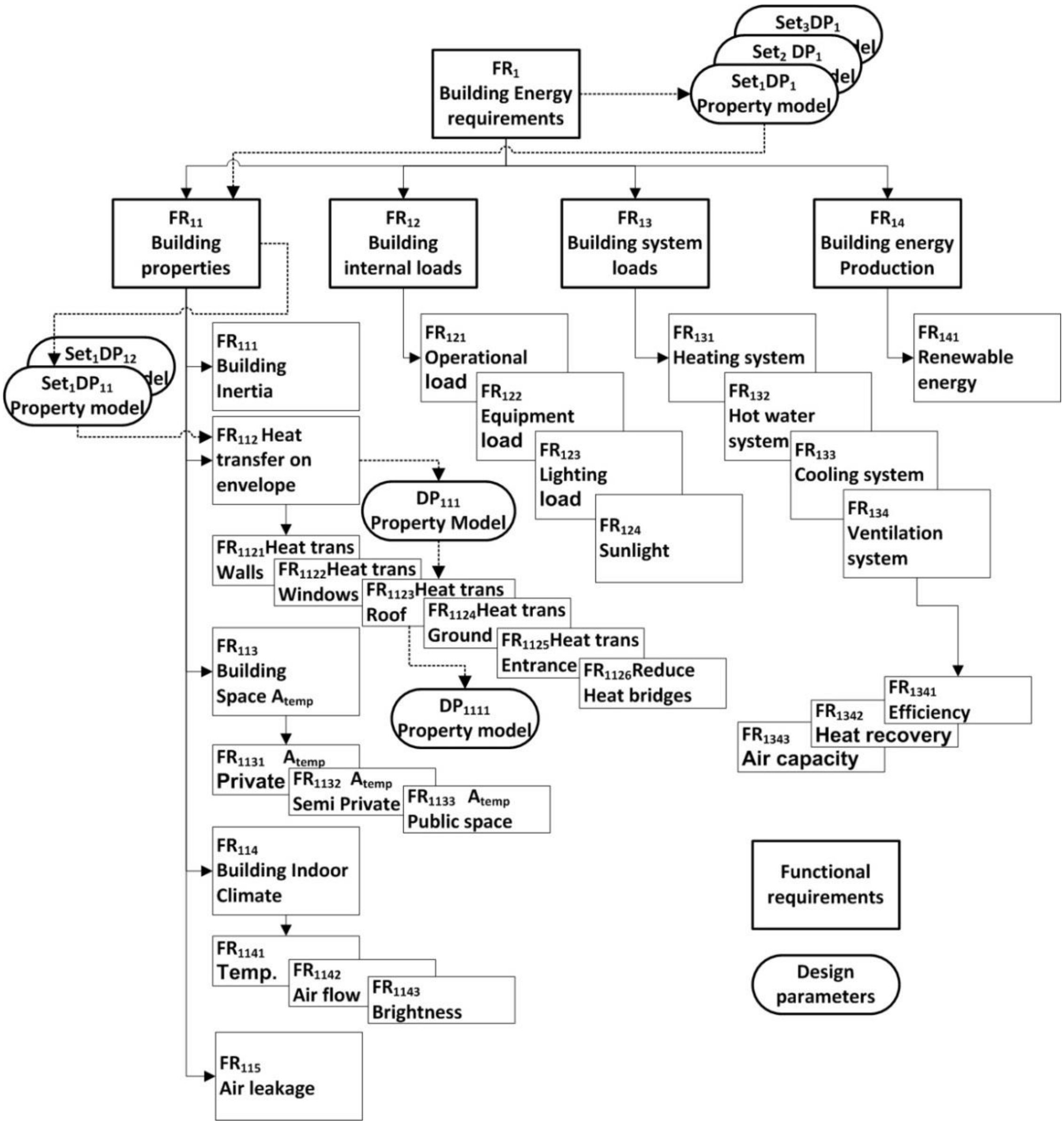

FIG 6 Energy requirements model

National and user requirements for the energy consumption of buildings can be mapped using different systems and components, such as the building envelope, internal gains and loads, consumption of HVAC system and the like (Cavique and Gonçalves-Coelho 2009). The common BIM requirements, developed by Senate Properties, describe a stage-gated strategy for the analysis of indoor comfort and for energy consumption (COBIM 2012). Combining Malmqvist´s (2001) anomalies (synthesis-analysis-evaluation) with the zigzag theory in axiomatic design, the energy requirements can be set up using the developed COBIM framework for energy, Fig 5. Here, the use of a Swedish classification system for building parts (BSAB 1990) will be used to enable exchange of information between design models and property models of energy (Ekholm and Fridqvist 1996). As this classification system is hierarchical, it is natural to arrange requirements in a matching hierarchy, according to the theory of axiomatic design, Fig. 6. The decomposition of energy requirements develops from both parent requirements and design parameters in the property model, Fig 6. The property model can be used to evaluate whether the performance of the design solution meets the functional requirements (Malmqvist 2001).

5. CASE STUDY

The design process at the case study company is divided into four stages: *conceptual design, schematic design, design development* and *detailed design*. A review of the design solution was conducted between each stage in the design process in respect of the requirements from the client and national codes. In the last three stages, energy simulation of 3D property models was carried out to secure the requirements for energy consumption. Even though energy simulation was part of the schematic design stage, the structural engineering work determined the progress of the design process.

5.1 Schematic design

The first energy simulation was conducted at the schematic design level, comparing different designs of the building envelope. The requirements (FRs) were determined by the Swedish code BBR15 (2008:20) and the local policy in Gothenburg, the constraints (Cs) by the location, geometrical and structural constraints and certain assumptions regarding input data not yet defined. Since only information regarding gross areas, location and building type was determined at this stage, a simplified simulation based on standard values was created for the purpose of checking basic requirements as well as to support decisions about the selection of energy supply. The simulation software IDA ICE (Fig 7) was used, in combination with a simple sensitivity analysis.

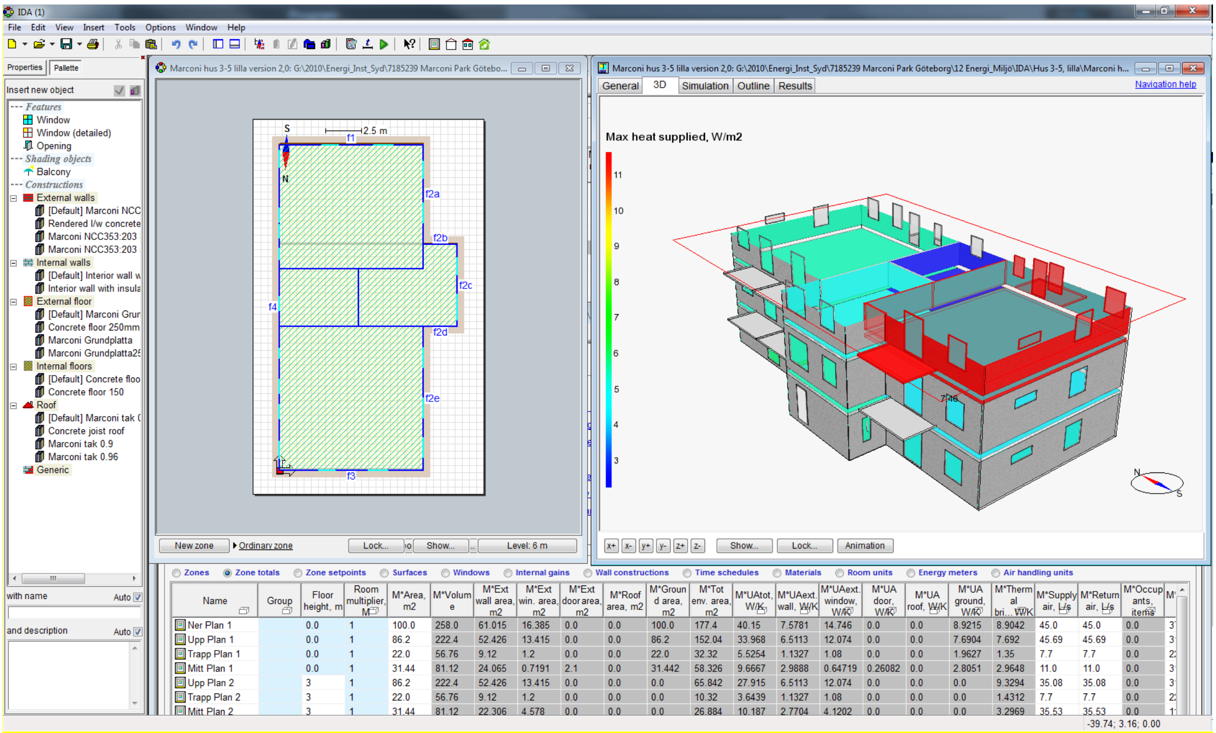

FIG 7 IDA Indoor Climate and Energy with the case study building

Two different building shapes were evaluated, slab block (Fig 7) and tower block, to ensure that the consumption and installed effect did not exceed 60kWh/m^{2}a and 15 W/m^2 respectively, according to the requirements of the city of Gothenburg (Gbg). The air leakage was set to 0.6l/sm^2 at 50 Pa as defined by the regulations. The heat transfer coefficient of the building envelope was estimated to be U=0.3 W/m^2 K where the proportion of thermal bridges was set to 15%. Estimation of ventilation losses was based on a ventilation rate of 0.35 l/sm^2 using two heat recovery systems installed in the ventilation system. A duct ventilation system with no heat recovery was compared with a system that delivered a heat recovery rate of 75%. It was assumed that the building will use district heating.

TABLE 1 Examples of FRs, Cs and DPs at the Schematic design level

FR	**Cs**	**DP**
FR_1= $Q_{energy} \leq 60$ kWh/m^{2}a (Gbg)	Cs= Climate data Gothenburg	Set_1DP_1 = Slab block A_{temp} = 1550 m^2 => Q_{energy} 58.2 kWh/m^{2}a
FR_{112} =$U_{total} \leq 0.5$W/m^{2}K (2008 BBR 15)	Cs= Open space structural limits	Set_2DP_1 = Tower block A_{temp} = 1400 m^2 => Q_{energy} 62.4 kWh/m^{2}a
FR_{114} = Indoor climate (Gbg)	Cs = Levels 2860 mm	
FR_{1142} = Ventilation rate ≥ 0.35l/sm^2		DP_{112} = Building envelope U_{total} = 0.3W/m^{2}K
FR_{1143}= Bright energy-efficient flats		DP_{1122} = Wall Brick 200 insulation U=0.16 W/m^{2}K
FR_{115} = Air leakage ≤ 0.6l/sm^2 at 50 Pa		Set_1DP_{1142} = Duct systems without heat recovery
FR_{131} =Heating performance ≤ 15W/m^2(Gbg)		Set_2DP_{1142} = Duct systems with heat recovery
		DP_{1143}= Attic flats
FR_{213} = 10% ≤ windows to net gross area (2008 BBR 15)		DP_{213} = 18% windows to the net gross area (A_{temp})

The tower block shaped building (280 m^2/floor plan) was less energy-efficient (62 kWh/m^2a) than the slab block building (310 m^2/floor plan, 58 kWh/m^2a). This difference between building shape was restricted to the number of buildings and five floor plans from the city plan. However, the recommendation from the energy analysis team was that both building types could be adapted to meet the energy requirement. The solutions were primarily evaluated from a city plan perspective and not from energy performance at this stage. The team also recommended windows with a lower heat transfer coefficient and that the air leakage be reduced. Changing to a ventilation system with no heat recovery increases the energy demand by 37kWh/m^2a. At the end of this design stage, a decision to continue only with the slab block building was taken from the layout of site area without analysing the glazing area parameter**.**

5.2 Design development

In the design development stage, standardized spaces (i.e. shafts and toilets) and wall thickness were added to the list of Cs as constraints of the building system along with the storey size. In the second energy simulation, the building shape, the structure and the orientation to the sun were defined. These DPs are represented by space elements in the property model. The heat transmission coefficients (U-value) for the different components in the building envelope e.g. window, walls, roof and floor slab, were set according to the recommendations in the BBR. The sensitivity analysis showed that a change of the heat transfer coefficient for windows from 0.9W/m^2K up to 1.1W/m^2K would increase the energy demand by 2.5 kWh/m^2a. Also, the size and placement of windows, which affects the heat gains through the incoming solar radiation, were considered in the simulation. The glazing U-values, solar properties and external shading effect on energy consumption were analysed. The location of windows and walls facing different orientations were defined.

TABLE 2 Examples of FRs, Cs and DPs at the Design development level

FR	**Cs**	**DP**
FR_1= $Q_{energy} \leq 60$ kWh/m^2a (Gbg)	Cs= Climate data Gothenburg	Set_1DP_1= Slab block A_{temp} = 1284m^2=>Q_{energy} 57.9 kWh/m^2a
FR_{112} =$U_{total} \leq 0.5$ W/m^2K (2008 BBR 15)	Cs= Shading of the building	Set_2DP_1= Slab block A_{temp} = 1284m^2=>Q_{energy} 60.4 kWh/m^2a
FR_{1121}=$U_{walls} \leq 0.18$ W/m^2K	Cs= Levels 2860 mm	
FR_{1122}=$U_{windows} \leq 1.3$ W/m^2K (2008 BBR 15)	Cs= Structural wall 200 mm conc.	DP_{112}= Building envelope U_{total} = 0.27 W/m^2K
FR_{1123}= $U_{roof} \leq 0.13$ W/m^2K	Cs= Open space structural limits	DP_{1121}= 50+195+70 mineral wool U_{walls} =0.124 W/m^2K
FR_{1124}= $U_{ground} \leq 0.15$ W/m^2K		Set_1DP_{1122}= Frame windows U_{window} =0.9 W/m^2K
FR_{114} = Indoor climate (Gbg)		Set_2DP_{1122}= Frame windows U_{window} =1.1 W/m^2K
FR_{1142}=Ventilation rate $\geq$ 0.35l/sm^2		DP_{1123}= Roof U_{roof} =0.94 W/m^2K
FR_{1143}= Bright energy-efficient flats		DP_{1142}=Duct system 0.5 l/sm^2
$FR1_{115}$ =Air leakage $\leq$ 0.6l/sm^2 at 50 Pa		DP_{1143}=Two attic flats with dormers
FR_{131}= Heating performance 15W/m^2 (Gbg)		DP_{1241}= 6.1 % south facing windows
FR_{213} = 10% $\leq$ windows to net gross area		DP_{1242}=79.2 m^2 south facing windows
(2008 BBR 15)		DP_{213} = 12.5 % windows to the net gross area (A_{temp})
		DP_{2131}=160.4 $m^2$of windows

In the building design stage, a more detailed energy simulation was conducted. Factors such as ventilation losses through window openings or air exhausts were included.

5.3 Detailed design

In the detailed design phase, the analyses of energy performance and indoor climate simulation were carried out to verify that the final design (DP) fulfilled the requirements (FRs), see table 3. During the design process, the national regulations were updated to BBR19 (2011:26), changing the requirements of the U-values. At this stage of the design of the heating loads, the energy use of cooling loads and heat generation was defined. Furthermore, building parts were defined to component level and validated in the energy simulation. The roof solution became one critical factor for the resulting energy demand with a late structural design of a glulam roof combined with dormers for attic apartments that resulted in a high U-value (0.94 W/m^2K). The specific space layout was defined and simulations of indoor climate for different ventilation systems were conducted.

TABLE 3 Examples of FRs, Cs and DPs at the Detail design level

FR	Cs	DP
FR_1= $Q_{energy} \leq$ 60kWh/m^2a (Gbg)	Cs= Climate data Gothenburg	DP_1 = Slab block A_{temp} = 1284m^2=> Q_{energy} 57.9 kWh/m^2a
FR_{112} =$U_{total} \leq$ 0.4 W/m^2K (2011 BBR 19)	Cs= Shading of the building	DP_{112} = Building envelope U_{total} = 0.27 W/m^2K
FR_{1121}=$U_{walls} \leq$ 0.18 W/m^2K	Cs = Levels 2860 mm	DP_{1121}= 50+195+70 mineral wool U_{walls} =0.124 W/m^2K
FR_{1122}=$U_{windows} \leq$ 1.2 W/m^2K (2011 BBR 19)	Cs= Structural wall 200 mm conc.	DP_{1122}= Frame windows U_{window} =0.9 W/m^2K
FR_{1123}= $U_{roof} \leq$ 0.13 W/m^2K	Cs= Max air Velocity/losses in ventilation duct	DP_{1123}= Roof U_{roof} =0.94 W/m^2K
FR_{1124}= $U_{ground} \leq$ 0.15 W/m^2K	Cs= Storey dimension limits	DP_{11231} = Ceiling high 2.4m
FR_{1125}=$U_{entrance} \leq$ 1.2 W/m^2K (2011 BBR 19)	Cs= Open space structural limits	DP_{11232} = Roof structure U_{roof} =0.94 W/m^2K
FR_{1141} = Indoor climate (21ºC) (Gbg)		DP_{11233}= Roof insulation 450 mm mineral wool
FR_{1142} = Ventilation rate $\geq$ 0.35l/sm^2		DP_{11234}= Roof structure with glulam beams 90x495mm
FR_{1143} = Bright energy-efficient flats		DP_{1142} = Duct system 0.5 l/sm^2 (Mechanical exhaust air ventilation system with heat recovery)
FR_{115} = Air leakage $\leq$ 0.6l/sm^2 at 50 Pa		DP_{1143} = One three-room 101 m^2 and one two-room 71 m^2 attic flat
FR_{131} = Heating performance $\leq$15W/m^2(Gbg)		DP_{115} = Taped plastic film between floors and curtain walls
FR_{213} = 10% $\leq$ windows to net gross area (2011 BBR 19)		DP_{1241}=1.2 % south facing windows of A_{temp}
FR_{ij} = Requirements		DP_{1242} = 15.2 m^2 south facing windows
		DP_{131} = Heating system 14.1 W/m^2
		DP_{213} =12.5 % windows to the net gross area (A_{temp})
		DP_{2131} =160.4 $m^2$of windows
		DP_{ij} = Properties to spaces, components and systems

The size of ventilation systems was compared to the energy use of different ventilation and cooling systems, such as variable air volume and chilled beams. Here, air quality levels could also be improved or degraded with a resultant effect related to parameter changes in energy consumption, equipment sizing and thermal comfort. Also, the indoor climate at room level could be simulated for design values (DPs) by the input of requirements (FRs) when the detailing of structural and installation system had been defined. According to the energy engineer, the energy simulations were used to secure minimum requirements and were not used for optimization of energy performance until the *detailed design*.

6. ANALYSIS

6.1 Structure and transparency

The energy performance did not govern the design process, even if the energy requirement was prioritized by the client. The evaluation of energy performance was carried out on demand by the structural engineering team. The use of a stage-gate process increased the fulfilment of the requirements but the effects on the workflow were believed to be marginal according to interviews. The structure of axiomatic design with FRs, Cs and DPs was useful when visualizing inputs for decisions and analyses both in the early and later stages of the design process.

The identification, communication and decomposition of FRs, DPs and Cs broadly followed the proposed framework for quantitative requirements such as the heat transfer for the building envelope (FR_{112} > FR_{1121} , FR_{1122}). This visibility helped in updating the energy requirements from BBR 15 to BBR 19 when the codes changed during the detailed design phase. However, this structure was only visible to the energy design team and for the setting up of the property model and conducting of the analysis. Qualitative requirements such as *bright and energy-efficient apartments* (FR_{1143}) and *indoor climate* (F_{114}), were not decomposed and traced in the same manner as the quantitative requirements. Hence, "non-measurable" qualitative requirements lack a structure to refine their management throughout the design process (Attia et al. 2012).

6.2 Set-based or point-based iteration

The structural engineering team locked the design solution early in order to select efficient production methods. Hence, the set-based alternatives tested in the case study were limited to two building shapes (DP_1), two types of duct system (DP_{1142}) and windows with different U-values (DP_{1122}). According to the interviews, the management of multiple solutions was time-consuming.

Energy designers only participated in the three design phases where the results were used for the determination of structural dimensions and the design and selection of components and technical systems such as windows and the capacity of the ventilation system. Unplanned point-based iteration occurred in the phases *design development* and *detail design* when DP did not fulfil the energy FR. These extra iterations caused additional costs and delays (Le et al. 2012).

6.3 Space objects and functional requirements

When used as containers of functional requirements in BIM tools, space objects can be used to track FRs and Cs to manage design alternatives in the design process (Kiviniemi et al. 2005). It is also recommended by COBIM (2012) that design teams should use "*rough spatial models for alternative designs*". In the case study, only the energy requirements were mapped and made visible. According to interviews, the economic and resource risks increase if energy requirements and models were to be developed in the early design phase because of the uncertainty as to whether the project would ever be completed. However, the respondents also described early energy analysis for the evaluation of spatial requirements as being useful because of the opportunity it presents to assess the impact of the energy performance of the design solution and also the potential it has to reduce rework and non-value-adding iterations later in the design process. This equivocal attitude may be the reason for the relatively small involvement of the energy engineering team in specifying the functional requirements regarding energy and indoor climate, especially in the early design stages. The design team was more focused on the analysis of design solutions than the creation of a structure of functional requirements adapted to stakeholder values.

7. DISCUSSION

Kiviniemi (2005) wrote that the management of requirements in design is concerned with the verification of design solutions to a set of evolving requirements throughout the design process. High-level requirements that will be linked to the design need to be evaluated early in the design process. In the case studied, a gate ensuring that the functional requirements for energy were met at the schematic design stage was not set up. Also, the engineering activities for energy design were fragmented and mostly concerned with the analysis of the fulfilment of required properties of building parts and systems as proposed by the architectural and structural designers, rather than on activities based on a holistic view of a development of an energy efficient design. Operational islands, like the energy simulations performed in the case study, need to be connected to the other design disciplines by a framework with routines to enhance the transparency for the stakeholders and avoid sub-optimization along with unnecessary design iterations. Axiomatic design offers a structure to manage requirements and constraints in relation to design parameters (solutions) by systemizing them in a supporting structure. In the case study, areas other than energy such as fire, acoustics and environmental considerations also generated new requirements as the refinement of building design progressed.

Alternative design solutions were tested to some extent in the case study. However, the alternative design sets were few and rapidly abandoned in favour of one solution that progressed as a point-based design strategy. The opportunities to manage multiple solutions by using methods such as parametric 3D modelling and rough spatial models need to be developed in practice. The requirement structures derived from the theory of axiomatic design are of benefit for all stakeholders in building projects such as clients, project managers, suppliers and end-users (Ye et al. 2009). However, these structures need to be transformed between different views, connecting customer values with engineering design and production specifications (Malmgren et al. 2010; Jensen et al. 2012). Therefore, the use of spaces objects is recommended to communicate and transform client values into requirements.

Managing all the technical expertise required at the early design phase increases information complexity and can be time-consuming. Here, an integrated concurrent engineering approach, where functional requirements are centrally stored, decreases the non-value-adding iterations in the design process (Jallow et al. 2010) with a lower cost and higher quality as a result (Chachere 2009). The study of how energy requirements can be managed using the principals of the axiomatic design theory only shows a small part of how the theory can be applied to the design of buildings. In the axiomatic design structure, a client’s involvement and values need to be considered because, according to Kamara (1999), both qualitative and quantitative functional requirements are related to the voice of the customer.

8. CONCLUSIONS

This paper presents a framework based on the theory of axiomatic design to support the management of requirements in building design. By studying this framework within the context of managing energy requirements in the design of buildings, the following conclusions can be made:

- By identifying and making more transparent the functional requirements (client's, local and national regulations) and downstream constraints (from engineering, production and supply) in the design process, better support for selecting strategies and decision-making is created.
- A set-based design strategy together with the theory of axiomatic design can be used to manage and evaluate the performance of multiple design alternatives (DPs) against the established functional requirements (FRs).
- The proposed systematic requirement framework for energy performance can empower designers to consider and apply energy performance criteria right from the early schematic design stage.

The use of BIM to support the proposed requirement framework needs to be studied further and connected to construction classification and ontology. Also, further research is needed on how model-checking tools can be used to compare requirements (FRs) with the performance of design solutions and defined constraints (Cs). The use of FRs, Cs and DP structures can probably be reused as components with associated design and production activities. Finally, more research is needed on how to include other functional requirements in the proposed framework such as acoustic, environmental, moisture and fire requirements and how these can be managed concurrently throughout the design process.

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