REQUIREMENTS TRANSFORMATION IN CONSTRUCTION DESIGN

Gustav Jansson[a], Jutta Schade[b], Thomas Olofsson[b], Väino Tarandi[c]
[a]*Division of Structural Engineering, Luleå University of Technology S-971 87 Luleå, Sweden,*
[b]*Division of Architecture and Infrastructure, Luleå University of Technology S-971 87 Luleå, Sweden,*
[c] *Eurostep AB, Gravlundsvägen 137, S-167 51 Bromma, Sweden,*
gustav.jansson@ltu.se, jutta.schade@ltu.se. thomas.olofsson@ltu.se.

ABSTRACT

Transformation of performance requirements to technical solutions and production parameters is central for architects and engineers in the design process. Construction industry suffers from low efficiency in design, and the information flow creating bottlenecks for the production process. Tracing and managing information through design process needs standards both for requirements and Building Information Models in a life cycle perspective. Structuring functional requirements is of great interest for the construction industry and especially for companies developing industrialised housing system that often have control over the whole manufacturing process. The delivery of a new low-carbon economy in Europe puts pressure on the construction industry to reduce the energy consumption for buildings. Therefore is one national standard for energy requirements tested on a building system and evaluated in an Information and Communication Technology–environment (ICT) that supports the design process for industrialised construction. The result of the research shows that the transformation of requirements to technical solutions needs functionality that supports the design process by using standards for requirements. A rigid building system based on well defined design tasks together with a technical platform, both for spaces and physical elements, work as a backbone for development of ICT support systems. Product Life Cycle Support (PLCS), as a standard that enables flexibility in categorisation of information through the construction design.

Keywords: Requirements transformation, energy standards, BIM support, PLCS, construction design

1. INTRODUCTION

The architecture, engineering and construction industry suffers from the lack of supporting tools managing governmental regulations and client requirements in the design of buildings. Client's requirements are often not traceable through the design process and are often misinterpreted or lost in translation (Haymaker and Fischer 2008, Kiviniemi 2005). Also, the current practice of requirement management creates bottlenecks in the design process of industrialized construction (Jansson 2008).

From a life cycle perspective, late performed energy analyses in the design phase, limits the possibilities of energy optimisation and fulfilment of the energy requirements (Bazjanac 2009). Research on product models (more popular known as BIM) in the last decade has according to Amor (2009), strange enough led to less focus on life cycle management issues in the design process. ICT-system that supports the transformation of requirements into design solutions can also create a better and more holistic support of the life cycle perspective (Tarandi 2002). Here, the client as an active actor in the design team (Winch 2002, Bluyssen 2009), has an important role in the transformation of client values into design requirements in the early stages of the project. In order to increase the efficiency of the design from a life cycle perspective, a requirement structure is needed to support the design work (Almefelt 2005). Therefore, the use of Engineering Design theories can assist the transformation of functional requirements into design solution of large flexible systems in construction. Design methods for transformation of customer needs into products and solutions, adds value for the customer (Womack and Jones 1996). Axiomatic Design is such a theory from which matrix methods can be used to compare different design solution based on product models and checking of functional requirements (Suh 2001).

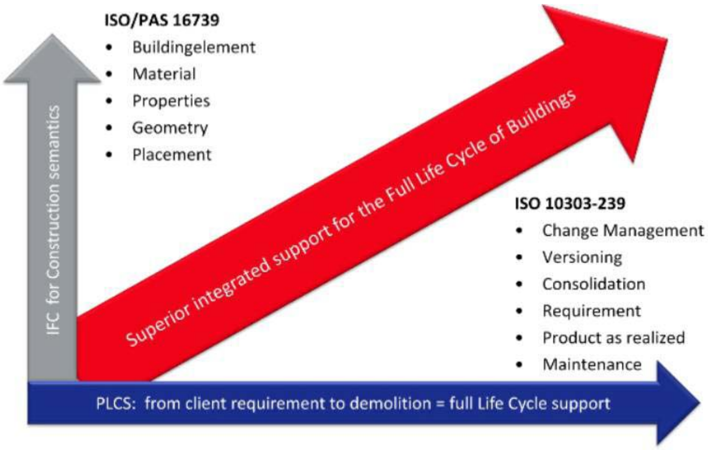


Figure 1. Combination of IFC and PLCS for Building Life Cycle Support (Eurostep, 2009)

International standards supports the exchange of information between different stakeholders over a product life-cycle (Tarandi 2003). The construction industry needs for sharing of building related information has resulted in the Industrial Foundation Classes for construction semantics (IFC ISO/PAS 16739 2009). For the Product Life Cycle Support, the PLCS standard, (ISO 10303-239 2009), is an information model based on ISO STEP that enables the creation and management through time and can therefore complement the Industry Foundation Classes IFC standard to provide a proper foundation for systems supporting building products over its whole life-cycle.

The aim of this paper is therefore to:

- define a requirements transformation framework for construction design based on requirements management and axiomatic design theory;
- demonstrate the requirements transformation framework to a proposed PLCS solution by using a energy requirements motivating case;

2. THEORY

2.1 Axiomatic Design Theory

Suh (2001) defines the Axiomatic Design Theory (ADT) as the mapping from "*what* we want to achieve" to "how we will achieve it". ADT is based on two axioms that governs the design process. The Independence Axiom states that always "maintain the independence of the Functional Requirements (*FR*s)". *FR*s are defined as the minimum number of independent functional requirements that characterize the design goals. The Information Axiom states that the best solution of the all solutions that fulfill the first axiom is the one that have highest probability of success. Suh (2001) defines the design as four domains transforming customers' attributes to functional requirements to design parameters and production variables in a sequence, figure 2. The transformation from one domain to the next is done by the use of design matrices, e.g. *FRs* = [**A**] *DPs* where [**A**] is the design matrix containing constants or functions connecting the functional requirements with the design parameters *(DPs)*.

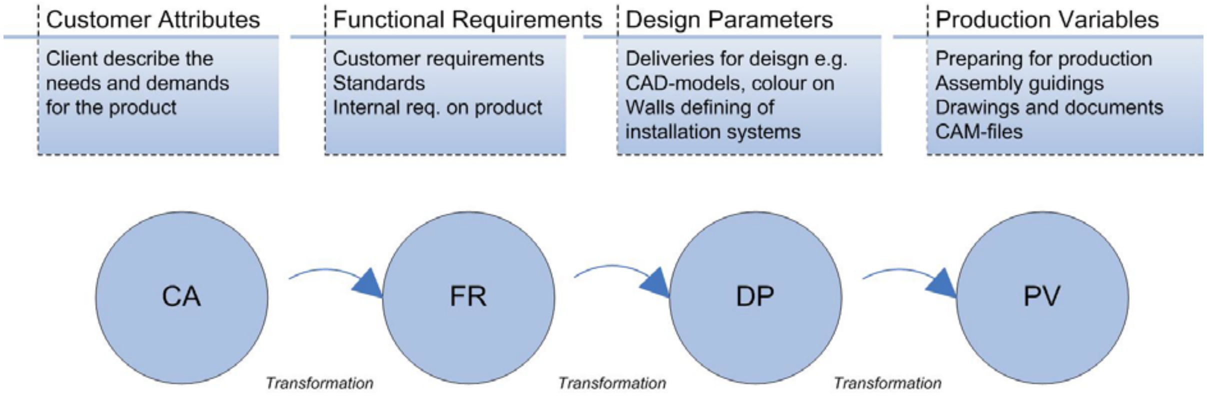


Figure 2. Design domains from customer needs to production variables, from (Suh 2001).

The focus of this paper is the mapping of Functional Requirements (FRs) to Design Parameters by decomposing of requirements using the "zigzag" method defined by Suhs (2001). The same methodology can be used to evaluate Production Variables (PVs) from DPs. Input and System Constraints (Cs) are bounds on solutions and all decisions from upstream (high level) design levels act as constraints at downstream levels (Suh 2001).

2.2 Requirement management

It is necessary for all stakeholders to define a requirement specification document in the product definition phase to enable traceability through the design process (Gumus 2005). System requirements is described by Stevens (1998) "what the system will do, but not how it will be done" and user requirements is the non technical definition of the whole product. With structured functions and requirements is product definition *Synthesised* by geometrical models and non-geometrical data in the requirements transformation process (Sutinen, et al. 2000). *Analysis* is done in external tools and methods for performance and properties. *Evaluation* is done to secure if the solution fulfil requirements. Separating user requirements from system requirements is necessary for checking completeness of the design through the product development phase (Stevens 1998). Also, to minimise the information flow it is recommended that each component has to fulfil the overall requirements to avoid translation through product hierarchies (Hull et al. 2005).

2.3 Product design and building system

Building systems for industrialised construction are defined as the collected experience and knowledge in how to realise a construction project (Söderholm 2010). Thus, a building system can be standardised both in technical solutions and in work methods. A Requirements Transformation Model (RTM) is suitable for process oriented organisation such as industrialised construction companies, (Jansson 2010). However, the RTM need to be implemented in a defined environment where the product specification gradually evolves from high level definition of FRs and DPs to low level FRs and DPs, (Suh 2001). Such a progress is proposed by Olofsson et al (2010), where the lifecycle of a building is describe in 7 maturity levels, of which the first four belong to the design phase; 0:Goals, 1:Conceptual, 2: Functional, 3:System, 4:Detailed, 5:As built, 6:Operation, 7:Demolition. For each maturity level, the higher level FRs and DPs from the previous maturity are decomposed in lower level FRs and DPs. The first step from maturity 0 to 1 include the transformation of Costumer Attributes (CAs) to high level FRs. Interfaces between work (planning, progress, conduct) and the product (spaces, systems, functions) are improved by the use of defined structures such as standards and classifications based on national or international standards (Ekholm, 2005). In cases where building systems contain modularised technical solutions, the detailed design can be automated to a large extent using parameterized modules, Jensen (2010).

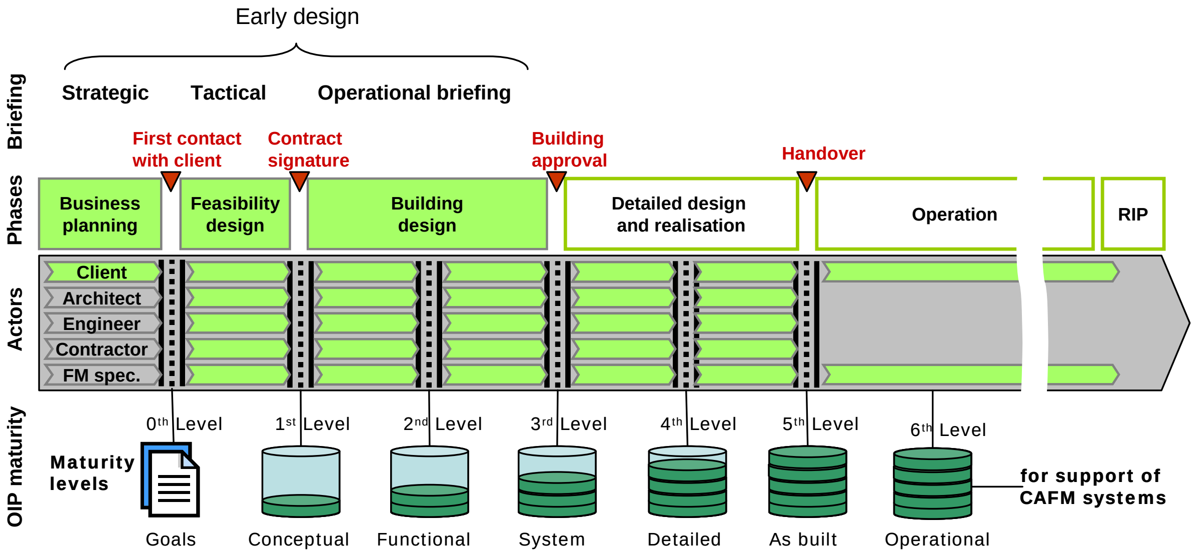


Figure 3. InPro stage gated concurrent design process, Olofsson et al (2010)

The concurrent design process is composed of parallel and sequential activities that could reuse more or less standardized workflows. Client's decisions at maturity gates also need to be based on more than one design alternative matching both user and system requirements, (Kam and Fischer 2004).

International standards for building components using the IFC-classification is based on ISO 12006-3. The national standards for parts in design for construction is BSAB, the Swedish standard for classification of spaces, building elements, and production results The building system can be visualised in different views from predefined categories. Kiviniemi, Fischer et al. (2005) defines levels of detail for a building system both in spatial categories (Project, Site, Building Stories, and Spaces) and in Product Systems (Circulation System, Structural System, Technical System, etc.) on physical-level. The IFC-classification enables items to have status both for spaces and in systems.

Functional requirements on national level is standardised in BBR (Construction rules) and BKR (Structural rules). BBR regulations are formulated in recommendation and obligatory rules by Boverket, who is the central government authority for building and housing. Energy requirements are described in BBR 16 in part 9:1 to 9:7 (Boverket 2008) and are formulated as minimum requirements for buildings in Sweden.

3. METHOD

A literature review in the theories field of engineering design, requirements managements and product development was conducted for the transformation phase in design for construction. The axiomatic design theory was selected as a base for the development of a requirements transformation framework for construction which implies separation of FRs and DPs, Suh (2001). The requirements transformation framework was secured by functionality in the proposed system BIM Collaboration Hub. The framework was demonstrated based on energy requirements taken from a real design project as a motivating case.

A simple student flat building with approximately 300m^2 and eight units situated in Malmö, Sweden was selected in the motivating case. This type of student hall of residence is manufactured at an industrialised housing company in need of support systems to speed up the design process, (Jansson 2008). The delivery of a new low-carbon economy in Europe also puts pressure on the construction industry to reduce the energy consumption and therefore limited energy consumption were our choice of requirements in the example.

4. REQUIREMENTS TRANSFORMATION FRAMEWORK

The functional domain is represented by national and client requirements (FRs). Attributes are connected to requirements as relations to functions, spaces, systems, versions, levels, etc. Constraints imposed by the building system are represented as boundary conditions and rules for manufacturing (Cs). Design parameters in the physical domain is represented in the early design and represented by parameters in a database and by hand also as virtual models of the building.

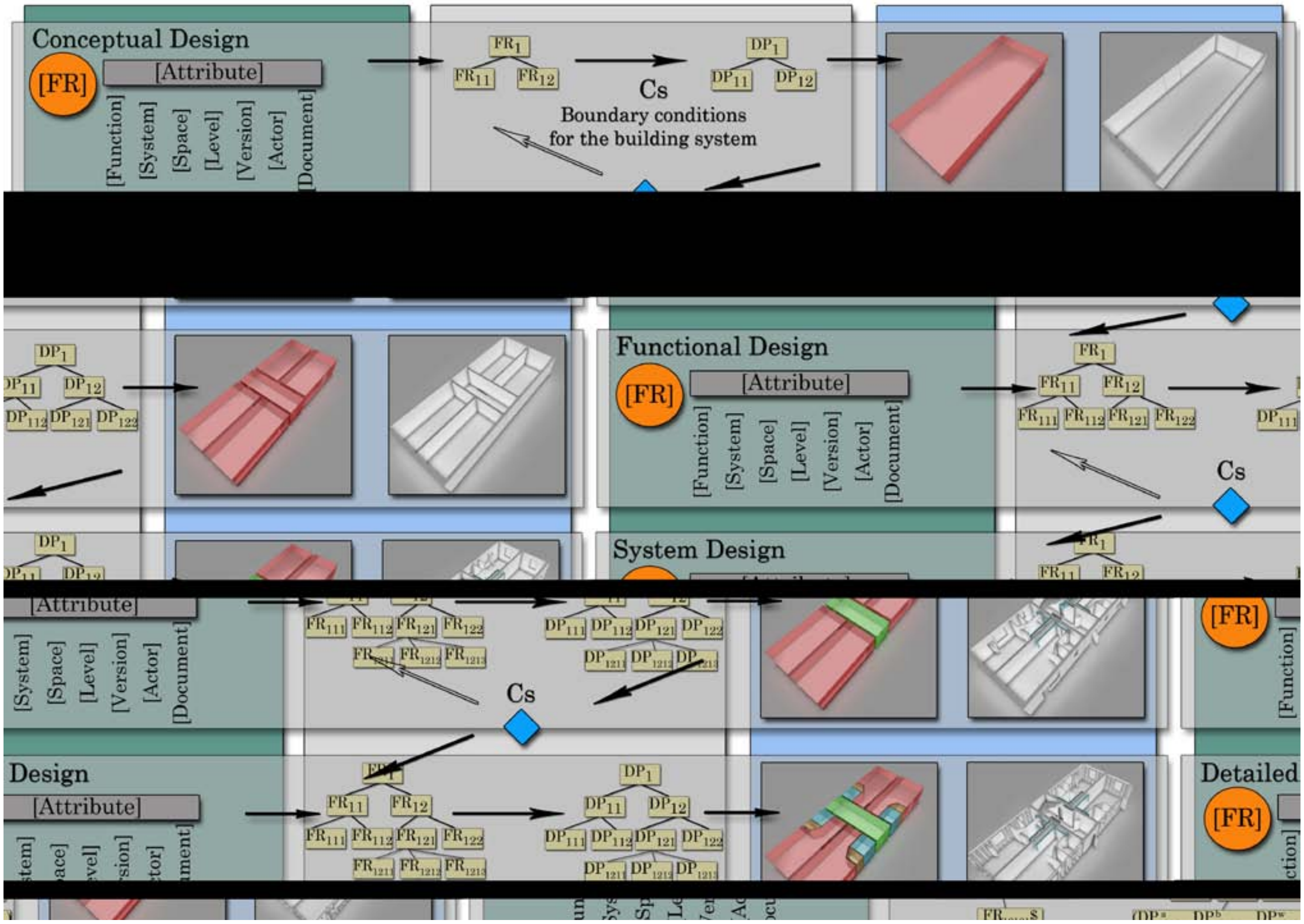


Figure 4. Requirements Transformation Model.

Four of the eight maturity steps proposed by InPro (Olofsson et al 2010) are represented by decomposition of FRs and DPs in the zigzag pattern between functional and physical domain in Figure 4. In the early maturity stages when physical elements and components is yet not part of the solution, DPs contain mainly spaces representing design alternatives stored in the hub in line with Kiviniemi's (2005) meaning about links between objects. Transformation of requirements to design parameters in a large flexible building system can be structured with type solutions in the knowledge database based on previous experience of instantiated solutions. In each of the transformation stages the decomposed requirements are checked against analysis and simulation results (ARs) of proposed design solutions. At each level actors meet in project defined quality gates (marked in blue) to select the best solution and enter the next maturity level. According to the information axiom the selected alternative should have the highest probability of success. However, it is up to the decision maker to make that judgment.

4.1 BIM Collaboration Hub

The Share-A-Space BIM Collaboration Hub is using PLCS as a backbone for the life cycle management of model objects. It is supporting open BIM objects represented by IFC semantics where the IFC objects are mapped to the PLCS data model and stored in the Hub as PLCS objects.

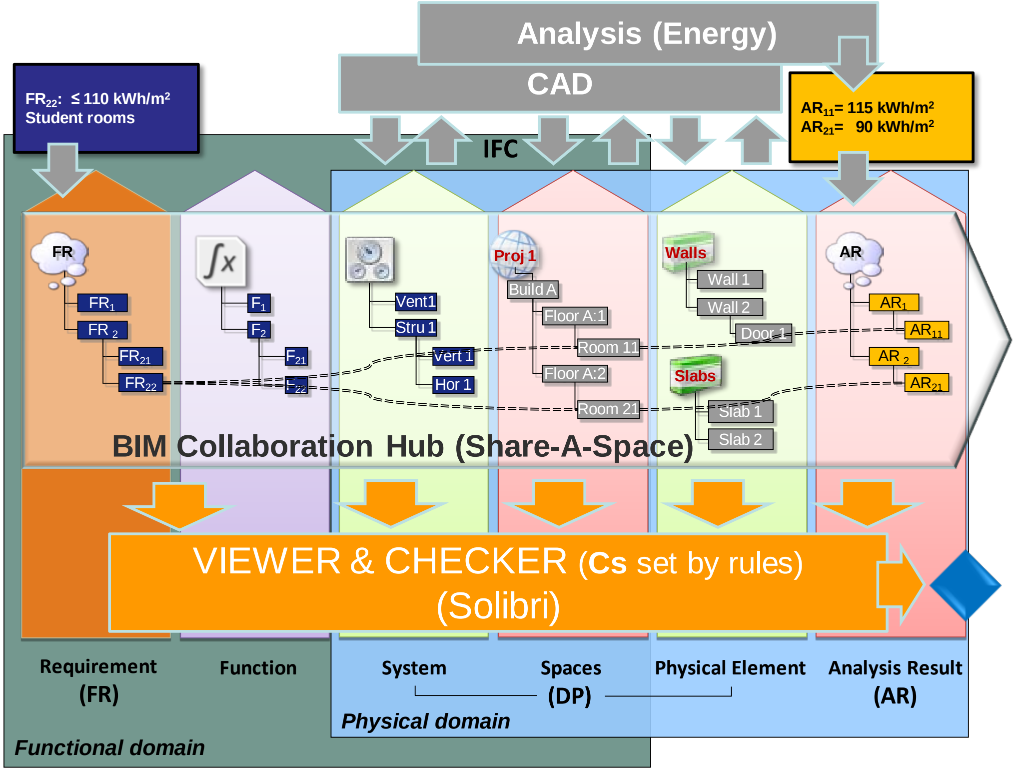


Figure 5. BIM Collaboration Hub services

Data exchange is typically based on check-out/check-in operations using partial models or even the full dataset. Access control and versioning on object level is part of the services provided by the Hub. Viewing and checking of requirements and rules linked to objects is enabled with the Solibri Viewer and Model Checker services built into the Hub, see Figure 5.The following step defines a typical stage-gated design process using the BIM collaboration Hub:

- Define/decompose high level functional requirements (FRs) for the current level of maturity in the Hub.
- From the defined FRs, determine a design strategy and create design alternatives.
- Upload design alternatives to the Hub (partial model exchange) using IFC exchange mechanism and link the FRs to the appropriate design objects (DPs)
- Depending on the maturity level, the different model objects (DPs) will be stored in three views, system, space and physical element view.
- Boundary conditions (Cs) are defined as rules or rule sets in the built-in the BIM Collaboration Hub and controlled in Solibri model checker.
- Download the different design alternatives in an IFC compliant energy analysis tool and perform energy analyses for each alternative.
- Upload the analysis result (ARs) to the Hub and link result to design objects (DPs)
- The model checker can now report deviations from requirements and the project manager has now the option to repeat the design loop or proceed to the decision gate leading to the next maturity level.

4.2 Workflow using maturity levels

A workflow can be defined in the BIM Collaboration Hub where the project manager can create work request to be sent to the actors in the design process. Figure 6 show the workflow for the conceptual design stage in the case study of management of energy requirements.

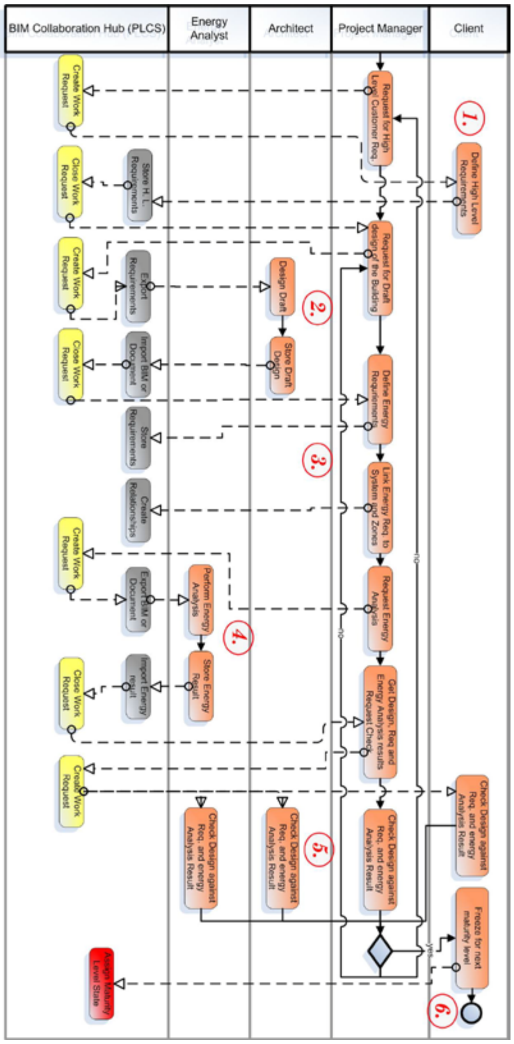


Figure 6. Workflow of Energy Analysis for Conceptual Design in the Requirements Transformation Model.

Six main activities are managed in the exemplified workflow: *1. Define High Level Requirements, 2. Design Draft, 3. Define Energy Requirements, 4. Perform Energy Analysis, 5. Compare Design against Requirements, Energy Analysis Results, and 6. Freeze Design solution for next level.*Each workflow is set-up for the reason of the specific level to control deliveries through process.

5. MOTIVATING CASE

The Requirements Transformation Model have been tested in a simple case study of a student flat building with approximately 300m^2 net gross area and eight units situated in Malmö, Sweden.

5.1 Maturity Level 1 - Conceptual Design

At the conceptual maturity level, design alternatives concerning placement and building envelope can be studied under consideration of the national regulation. The first energy estimation calculation can be done regarding the FR given by the Swedish regulations BBR16, the given DP and certain assumption of missing input data. At the Conceptual maturity level, FRs, Cs, DPs, and calculated results (ARs) are stored in the BIM Collaboration Hub to communicate and trace information for all disciplines. Since only information regarding gross areas, location and building type is known; simple estimates based on steady state calculations methods are proposed for the purpose of checking of requirements and decision support for the selection of energy supply, see Figure 8.

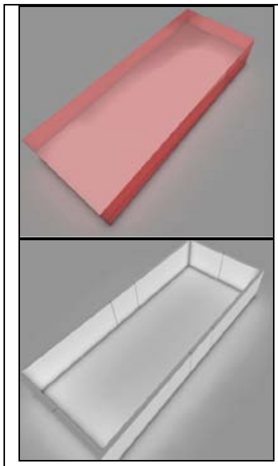
	$FR_1 = Q_{energy} \le 110$ kWh/m^{2}a $FR_2 = U_{total} \le 0{,}5$ W/m^{2}K FR_3 = ventilation rate $\ge 0{,}35$l/sm^2 FR_4 = air leakage $\le 0{,}8$l/sm^2 at 50 Pa	Cs=monthly average temp Malmö Cs=storeys dimension limits	DP_1 = ca.300 m^3 $DP_2 \ge 10\%$ windows to the net gross area DP_3 = ceiling high 2,4m DP_4 = 2 floors
	Energy calculation Result : Based on an steady state calculation with an average indoor temperature from 20°C and the required assumed input data the following result is uploaded **Alternative 1** AR_1= 88 kWh/m^{2}a by 0% heat recovery, AR_2= 0,43 W/m^{2}K **Alternative 2** AR_1= 67 kWh/m^{2}a by 50% heat recovery, AR_2= 0,43 W/m^{2}K **Alternative 3** AR_1= 50 kWh/m^{2}a by 0% heat recovery, AR_2= 0,17 W/m^{2}K **Alternative 4** AR_1= 31 kWh/m^{2}a by 50% heat recovery, AR_2= 0,17 W/m^{2}K		

Figure 8. Spaces and Physical elements at the conceptual level

Dependent on the selected alternative (1-4) it can be discussed if the requirement FR_2 shall be changed in the next maturity level.

5.2 Maturity Level 2. Functional level

The functional level building shape and structure are defined and also orientation to the sun is determined. These become DP's that is represented by space elements with traceable requirements in the BIM Collaboration Hub. The functional maturity level implies that the defined structure gives the heat transmission coefficient (U-value) for the different modules like window, walls, roof and floor slab.

Table 1. heat transmission coefficient

DPs	**Area [m^2]**	**U-value [W/m^{2}K]**
Wall south	77.4	0.18
Window south	20.5	1.6
Wall north	84.1	0.18
Window north	16	1.6
Wall west	36.3	0.18
Window west	5.7	1.6
Wall east	36.3	0.18
Window east	5.7	1.6
Roof	155.5	0.1
Floor slab	155.5	0.09
Total U-value		**U_{total} 0.25**

The size and placement of windows affects the heating gains via the incoming solar radiation. The glazing U-values, glazing solar properties and external shading may be altered and the change in energy consumption can be studied. Windows and walls facing in the different orientation direction could at this level be located as defined in the Table 1.

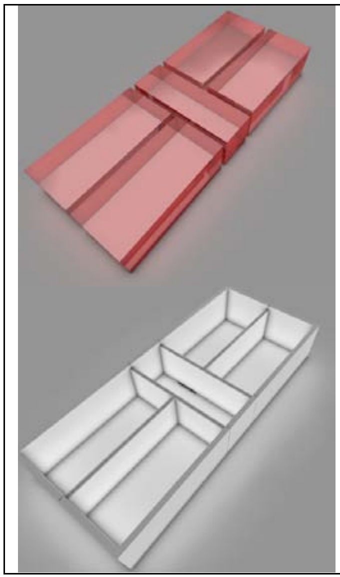
	$FR_1 = Q_{energy} \leq 110$ kWh/m^{2}a $FR_2 = U_{total} \leq 0.5$ W/m^{2}K $FR_{21} = U_{walls}$ $FR_{22} = U_{windows}$ $FR_{23} = U_{roof}$ $FR_{24} = U_{ground}$ FR_3=Ventilation rate ≥ 0.35l/sm^2 FR_4 =Air leakage ≤ 0.8l/sm^2 at 50 Pa	Cs=Climate data Malmö Cs=Shading of the building Cs=mm wall thickness Cs=storeys dimension limits Cs=open space structural limits	DP_1 =311 m^3 DP_2 =15% windows to the net gross area DP_{21}=43% south facing windows DP_{211} = 22.5m^2 south facing windows DP_{212}-DP_{21i}=m^{2}of windows DP_3 =ceiling high 2.4m DP_4 = 2 floors DP_5 =Building structure DP_{51}=wall structure DP_{52}=roof structure DP_{53}= ……..
	<u>Energy simulation Result:</u> Based on a dynamic energy simulation, with an average indoor temperature from 21°C, the required input data resulting out of the FR, Cs and DP's see table 1. and min. required ventilation system input data. **Alternative 1** AR_{11}= 110 kWh/m^{2}a by 0% heat recovery, AR_{21}= 0,25 W/m^{2}K **Alternative 2** AR_{11}= 83 kWh/m^{2}a by 50% heat recovery, AR_{21}= 0,25 W/m^{2}K **Alternative 3** AR_{11}= 70 kWh/m^{2}a by 70% heat recovery, AR_{21}= 0,25 W/m^{2}K		

Figure 9. Spaces and Physical elements at the functional level

Different alternatives regarding the heat recovering are studied as the simulated case with no heat recovering shows a result close to Q_{max} of 110 kWh/m^{2}a. Former studies show that at this maturity level an underestimation of the actual energy consumption can be in the order of 30%, (Schade, 2009).

5.3 Maturity Level 3. System level

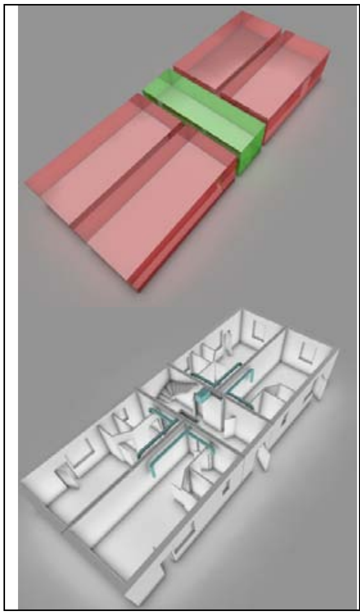
	$FR_1 = Q_{energy} \leq 110$ kWh/m^{2}a $FR_2 = U_{total} \leq 0.5$ W/m^{2}K $FR_{21} = U_{walls}$ $FR_{22} = U_{windows}$ $FR_{23} = U_{roof}$ $FR_{24} = U_{ground}$ FR_3 = ventilation rate ≥ 0.35l/sm^2 FR_4 = air leakage ≤ 0.8l/sm^2 at 50 Pa	Cs=Climate data Malmö Cs=Shading of the building Cs=mm wall thickness Cs=storeys dimension limits Cs=open space structural limits	DP_1 =311 m^3 DP_2 =15% windows to the net gross area DP_{21}= 43% south facing windows DP_3 =ceiling high 2.4m DP_4 = 2 floors DP_5 =Building structure DP_{51}=wall structure DP_{52}=roof structure DP_{53}= …….. DP_6 =mechanical exhaust air ventilation system DP_7 =Ventilation system capacity DP_8= space zoning
	<u>Energy simulation Result:</u> Based on a dynamic energy simulation with a range of indoor temperature from 20-24°C the required input data resulting out of the FR, Cs and DP's see table 1., and further defined ventilation system input data. **Alternative 1** AR_{12}= 107 kWh/m^{2}a by 0% heat recovery **Alternative 2** AR_{12}= 82 kWh/m^{2}a by 50% heat recovery **Alternative 3** AR_{12}= 72 kWh/m^{2}a by 70% heat recovery		

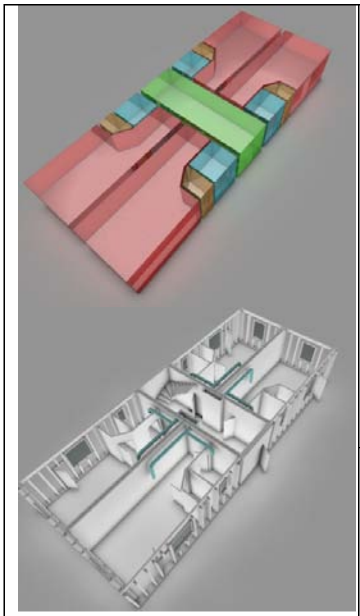
Figure 10. Spaces and Physical elements at the System level.

As for the previous described levels, a workflow can be defined for the System level to control tasks and information sharing through the design process at the system level. In this phase the specific space layout is defined and simulations according indoor climate for different ventilation systems is suggested, see Figure 10. Dimension of ventilation system is compared to energy consumption of different ventilation and cooling systems, such as variable air volume and chilled beams. Air quality levels could be improved or downgraded with a resultant effect, that is related to parameter changes in energy consumption, equipment sizing and thermal comfort. Also, the indoor climate on room level can be simulated and design values (DPs) and requirements (FRs) for the detailing of structural and installation system can be defined.

5.4 Maturity Level 4. Detail level

In the detailed design and realisation phase the analyses of energy performance and indoor climate simulation are made for verification of the final design, see Figure 11:

- *Space detail definition:* Design solution specified for heat loads, cooling loads, energy use and heat generation. Validate energy consumption for the specified layout.
- *Physical element detail definition:* Validation by simulation for system definition down to component level regarding indoor climate and energy loads.

<table>
<tr>
<td rowspan="2"></td>
<td>$FR_1 = Q_{energy} \leq 110$ kWh/m^{2}a
$FR_2 = U_{total} \leq 0.5$ W/m^{2}K
$FR_{21} = U_{walls}$
$FR_{22} = U_{windows}$
$FR_{23} = U_{roof}$
$FR_{24} = U_{ground}$
FR_3 = ventilation rate ≥ 0.35l/sm^2
FR_4 = air leakage ≤ 0.8l/sm^2 at 50 Pa</td>
<td>Cs=Climate data Malmö
Cs=Shading of the building
Cs=mm wall Thickness
Cs= max air Velocity/ losses in Ventilation duct
Cs=storeys dimension limits
Cs=open space structural limits</td>
<td>DP_1 =311 m^3
DP_2 =15% windows to the net gross area
DP_{21}=43% south facing windows
DP_{212}-DP_{21i}=m^2 of windows
DP_3 =ceiling high 2.4m
DP_4 = 2 floors
DP_5 =Building structure
DP_{51}=wall structure
DP_{52}=roof structure
DP_{53}=
DP_6 =mechanical exhaust air ventilation system
DP_{61} =Ventilation components
DP_7 =Ventilation system capacity
DP_{71}= Vent. component capacity
DP_8=space zoning
DP_{ij} =Components</td>
</tr>
<tr>
<td colspan="3"><u>Energy simulation Result:</u>
Based on a dynamic energy simulation with a range of indoor temperature from 20-24°C the required input data resulting out of the FR, Cs and DP's see table 1., and further defined ventilation system input data.

Alternative 1
AR_{13}= 109 kWh/m^{2}a by 0% heat recovery
Alternative 2
AR_{13}= 80 kWh/m^{2}a by 50% heat recovery
Alternative 3
AR_{13}= 73 kWh/m^{2}a by 70% heat recovery</td>
</tr>
</table>

Figure 11. Spaces and Physical elements at the Detail level.

6. CONCLUSIONS

In this paper a Requirements transformation framework was defined based on the axiomatic design and requirements management, where FRs and DPs are separated in the design of building system as gate controller. A well defined Building System can minimise iterations (zigzagging) in the design if the boundary conditions and clearer functional requirements are defined and supported early in the design process. Defining different maturity levels in framework based design is not evident due to lack of experience and proof of concept in the construction industry but is valuable to control design progress.

Energy requirements and results from energy analyses are examples that are define and link to design objects in the BIM Collaboration Hub. The axiomatic definition of the functional domain represented by requirements linked to attributes of physical, space, function objects of different maturity and versions can be used already in the early design phase for a better product solution.

Building systems and common practice in construction design do not often detail the design solution into components at the level of articles. The IFC specifications are based on product modelling for collaboration between actors and have the geometrical model as part of the information carrier. The PLCS standard is based on neutral entities and is flexible and adaptable to manage all types of information for all participants in the design phase and defined workflows could be managed on task level for design in the solution of BIM Collaboration Hub.

The proposed theoretical framework facilitates requirements management, however the transformation from client demands to requirements and mapping these requirements are not solved within this framework. The BIM Collaboration Hub, as a PLM system, should be tested in a multi-disciplinary environment to secure the functionality and user interface in real projects.

ACKNOWLEDGEMENT

The result presented in this paper is partly the result of the InPro (http://www.inpro-project.org) - an integrated project funded by the European Union 6th framework program.
The research is also be founded from the competence center of LWE (http://www.ltu.se/lwe).

REFERENCES

Almefelt, L. (2005). Requirements-driven product innovation : methods and tools reflecting industrial needs. Göteborg, Chalmers tekniska högskola.

Bazjanac, V. (2009). CIB-W78, 26th International Conference, Managing IT in Construction, Istanbul.

Bluyssen, P.M. (2009) Capturing Stakholder Values State of the art study, Public Report of Deliverable D14a, The InPro project, available at http://www.inpro-project.eu/publications.htm

Boverket, B. (2008). "Regelsamling för byggande, BBR." from http://www.boverket.se/.

Ekholm, A. (2005). "ISO 12006-2 and IFC–Prerequisites for coordination of standards for classification and interoperability." Journal of Information Technology in Construction 10: 275-289.

Gumus, B. (2005). Axiomatic product development lifecycle, Citeseer.

Haymaker, J. and Fischer M. (2008). "Formalizing Narratives to Better Communicate & Integrate Sustainable Design Processes & Information."

Hull, E., Jackson K., et al. (2005). Requirements engineering, Springer Verlag.

ISO-10303-239 (2009). Product Life Cycle Support, PLCS, Eurostep Group, OASIS Product Life Cycle Support (PLCS) Technical Committee.

Jansson, G. and Helena J. (2010). "Evaluation of product life cycle management in industrialised housing design." Computers in industry.

Jansson, G. and Söderholm, E. (2008). Design Process Organisation at Industrial House Builders. Proceedings 24th Annual ARCOM Conference : 1-3. Cardiff, UK.

Jensen, P. (2010), Configuration of Modularised Building Systems, Licentiate Thesis, Luleå University of Technology, ISBN 978-91-7439-108-4.

Jørgensen, B. and Emmitt S. (2009). "Investigating the integration of design and construction from a "lean" perspective." Construction Innovation 9(2): 225-240.

Kam, C. and Fischer M. (2004). "Capitalizing on early project decision-making opportunities to improve facility design, construction, and life-cycle performance—POP, PM4D, and decision dashboard approaches." Automation in construction 13(1): 53-65.

Kiviniemi, A., Fischer M., et al. (2005). Multi-model Environment: Links between Objects in Different Building Models.

Kiviniemi, A. (2005), Requirements management interface to building product models, doctoral thesis, CIFE Technical Report #161, Stanford University

Olofsson, T., Schade, J., Meiling, J., Heikkilä, K., Dehlin, S., Benning, P., Schunke, M., Tulke, J., Schreyer, M., Sormunen, P., Holopainen, Hirvonen, T., (2010), The InPro Lifecycle Design Framework for Buildings, Public Report of Deliverable D17, The InPro project, available at http://www.inpro-project.eu/publications.htm

Schade, J. (2009). Energy Simulation and Life Cycle Costs. Licentiate thesis, Luleå University of Technology.

Stevens, R. (1998). Systems engineering: coping with complexity, Prentice Hall PTR.

Suh, N. (2001). Axiomatic design, Oxford university press.

Söderholm, E. (2010). Applicability of Continuous Improvements in Industrialised Construction Design Process, Licentiate thesis, Luleå, Luleå University of Technology.

Tarandi, V. (2002). Implementering av produktmodeller baserade på IFC och BSAB, ITBoF2002, http://www. itbof. com.

Tarandi, V. (2003). Editorial: IFC-product models for the AEC arena, ITcon.

Tarandi, V. and Houbaux, P. (2010), Open Web-based ICT Platform, Public Report of Deliverable D20 p, The InPro project, available at http://www.inpro-project.eu/publications.htm

Winch, G. (2002). Managing construction projects : an information processing approach. London, Blackwell.

Womack, J. P. and Jones, D.T. (1996). Lean thinking : banish waste and create wealth in your corporation. New York, Simon & Schuster.