System-Embedded Building Design and Modeling

Parametric systems modeling of buildings and their environment for performance-based and strategic design

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Abstract. *The paper proposes Parametric Systems Modeling (PSM) as a tool for building and city planning. The outlined method is based on the Systems Modeling Language (SysML) and is intended for design, dimensioning, and optimization of buildings and cities as systems. The approach exceeds the geometric approach, considers additional information from physics, technology, as well as biology, and provides a basis for multidisciplinary analyses and simulations. Its application aims at the exploration of innovative sustainable design solutions at system level. The proposal of an innovative building-greenhouse-city system serves to illustrate the approach. Features of this system are closed water cycles, renewable energy use, thermo-chemical energy storage and transport of energy for heating and cooling purposes on the base of desiccants, as well as recycling of* CO_2*, accumulation of biomass and related soil improvement.*
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Introduction

The design of buildings and cities determines their environmental and economical performance to a high degree. However, current CAD practice in building design and modeling is usually limited to the subject of geometry and results in sequential decisions that do not consider the overall system with its interdependencies between the components. Existing models and applications handle additional non-geometrical information, such as integrated by Building Information Modeling (BIM), statically without allowing a dynamic parametric analysis and synthesis process.

To overcome these limitations, this paper proposes a new approach of Parametric Systems Modeling (PSM) for building and city design that exploits the system engineering approach for architectural and urban planning. PSM adds an additional view to the geometry-based view of current CAD as it allows to model flows of items and information and to define respective requirements. The intent of the new tool of PSM is to support the decision-making process by a discipline-integrative system model that describes the design artifact (i.e. the building in its environment) with its design requirements and considerations, allows a systematic exploration of the solution space, and makes decisions understandable by explicitly describing the interdependencies and determining the system performance of alternatives. This allows decision makers not only to consider the local effects within the building but also designing buildings in a strategic way by considering them being embedded in and interacting with their environment.

Systems Engineering in Design

The systems approach is of major importance for engineering design. Most modern artifacts strongly rely on the interaction with infrastructures, such as networks of ways, cables, plumbing, and other transport systems. Only by means of these infrastructures, the artifacts are able to perform in the desired way. Therefore, modern modeling requires the approach of systems engineering. For this purpose, the Systems Modeling Language (SysML, Object Management Group, OMG, 2008, [1]) provides a powerful tool for describing systems and their requirements, use contexts, and behavior. A main intent of the presented approach is to introduce SysML in building and city design.

SysML is equivalent to a top-down approach, whereas a bottom-up approach takes place as modeling environments of computer-aided design, engineering and manufacturing (CAx) increasingly include multidisciplinary information and analyses by the label of Product Lifecycle Management (PLM). Especially in the domain of mechanical design (e.g. aerospace and automotive engineering), parametric methods were developed that allow a parametric modeling process based on dependencies between parts. Up-to-date modeling environments (Catia, Pro/Engineer, and Siemens NX) use features and parametric dependencies not only for the geometric specifications of technical artifacts but also for additional non-geometric information for further analyses. However, they usually do not include an explicit system view.

In contrast, the methods of Multidisciplinary Design Optimization (MDO) explicitly use a systems approach for improving a design artifact by modeling it as a system crossing disciplinary borders. This allows to consider the performance of the design at early planning stages and to make strategic decisions. Furthermore, tools, such as parameter studies, sensitivity analyses, and many different optimization methods, allow to improve the design automatically provided that the model configuration is flexible and allows algorithmic generation of variants. Furthermore, the approach of the Design Structure Matrix (DSM [2], first described by Steward 1981) explicitly deals with the system and the improvement of its structure. However, a shortcoming of MDO is that information on the design synthesis, such as use cases, requirements, etc., are not included.

Adaptation of System Modeling for Buildings and Cities

In contrast to engineering design, the adaptation of parametric modeling in building design, which was recently introduced in practice by the leading AEC software companies (Autodesk, Bentley, and Gehry Technologies), strongly focuses on geometry and does not exploit the full potential of a discipline-integrative system view. Due to this reason, many designers associate parametric modeling in AEC with ambitious geometries. However, the potential of an integrative parametric system model, which represents the interdependencies between components and disciplines, is enormous. It can include analysis and simulation directly in the design, which results in a holistic dynamic model. By this, it connects engineering, economic, and environmental aspects to visual and geometric properties of a building design. This connection enables performance-driven and strategic design decisions.

To develop a method of PSM for building and city design, the first part of this paper introduces a design-oriented method of system development that enables the modeling of typical design synthesis and analysis situations on the basis of the above mentioned SysML. This provides a basis for explicitly describing design considerations and dependencies for analysis and interconnects them. The second part applies the approach to an innovative building-greenhouse-city system. First, this application gives a suitable example for the use of PSM. Second, it provides the basis for a methodological design process of this innovative system by explicitly describing the use, the requirements, and the interaction of the subsystems.

Paradigm shift: Design-oriented System Modeling

For enabling designers to use systems engineering in the design process, a paradigm shift towards a design-oriented systems approach is required. The descriptive method of classic systems theory that focuses on the analysis of systems needs novel structures that serves for both, for synthesis of designing and for analysis and simulation. Consequently, PSM for design needs to exhibit two essential model characteristics: First, the model needs component-oriented structures that allow to handle model parts interactively as practiced in the current CAD practice. Second, besides the pure static description of the actual state of the design, the representation of the design's use and its functional requirements need representation in the model for a dynamic systems approach.

Component-oriented modeling

Traditional MDO and the involved system modeling often proceed discipline-oriented, i.e. the system consists of discipline modules that represent each discipline's view. For designing, the rearrangement of components (building parts and city elements) is an essential operation of the design process. To support this process, it is required to structure the decomposition component-orientated: The model consists of components that represent the building parts and city elements and that are linked by parameters. Disciplines intersect within the components. Geyer (2009) presents an example for component-oriented decomposition and the application of MDO in building design by means of a hall example.

For the component-oriented decomposition of buildings and cities, further domain-specific modeling languages exist, that provide appropriate component structures:

- Industry Foundation Classes (IFC). The IFC (International Alliance for Interoperability, IAI, 2010, [3]) comprise definitions for modeling in building design, construction, and facility management and are a common base for Building Information Modeling (BIM). How to use and to extend this standard for component-oriented decomposition and for establishing a systems model for applying MDO is also described by Geyer (2009).
- City Geography Markup Language (CityGML). This modeling standard mainly focuses on the representation of cities and landscape. For buildings, it encompasses geometric information including definitions of indoor geometry, openings, windows, doors etc. and allows some additional non-geometrical information, such as materials and textual information. In contrast to the IFC, it focuses on visualization. Kolbe (2009) gives an overview of the language and its use.
- Green Building XML (gbXML). This language's intent is the definition and exchange of building models and their physical properties for applying energetical performance analyses and simulations. Its scheme [4] is limited to buildings like the IFC, but refines the definitions of the IFC with respect to the physical conditions (external conditions included), and omits non-physical information.

The combination of these domain-specific standards provides a set of components that supplements SysML for describing buildings and their embedding in cities. However, these standards do not guarantee compatibility. Therefore, the following system description does not use the standards directly, but they serve for orientation purpose.

Requirement-driven Functional Modeling

Besides the analysis-oriented system description with its matter flows etc., a paradigm shift towards a design-oriented description is necessary, which reflects the functional requirements of the design and, thus, allows to derivate variants methodically. This shift helps to overcome the static model description and enables a methodological development of the design. Traditional systems theory links parameters in the same way as the flow of items (e.g. energy, material, etc.). In contrast, design-oriented linking of components does not necessarily follow this direction but additionally uses a paradigm of function, requirement, and satisfaction; respective links might point in the opposite direction. The SysML provides a suitable framework for modeling these dependencies. Four diagram types serve for defining a system model for designing, as illustrated by Figure 1. They split up into three design-oriented views and one analysis-oriented view:

1. Use case diagrams (uc) describe how the system is typically used. They link the system and subsystems to actors and set application contexts.
2. Requirement diagrams (req) define the framework for the system's development by deriving requirements from the use cases.
3. Block definition diagrams (bdd) define the system structure by associations between the components (blocks). Furthermore, the proposed PSM method attaches the requirements to the associations between the components to obtain an expressive design-oriented system description. This modified diagram type is essential for designing since it links requirements to system parts and associations between them. Therefore, it represents the system in a requirement-driven functional view.
4. Internal block diagrams (ibd) describe the flows in the system. This view is equivalent to the classical systems theory and required for analysis and simulation (e.g. of the performance).

These four diagram types cover the switching of views typical for designing. The conventional systems view of the internal block diagram (ibd)

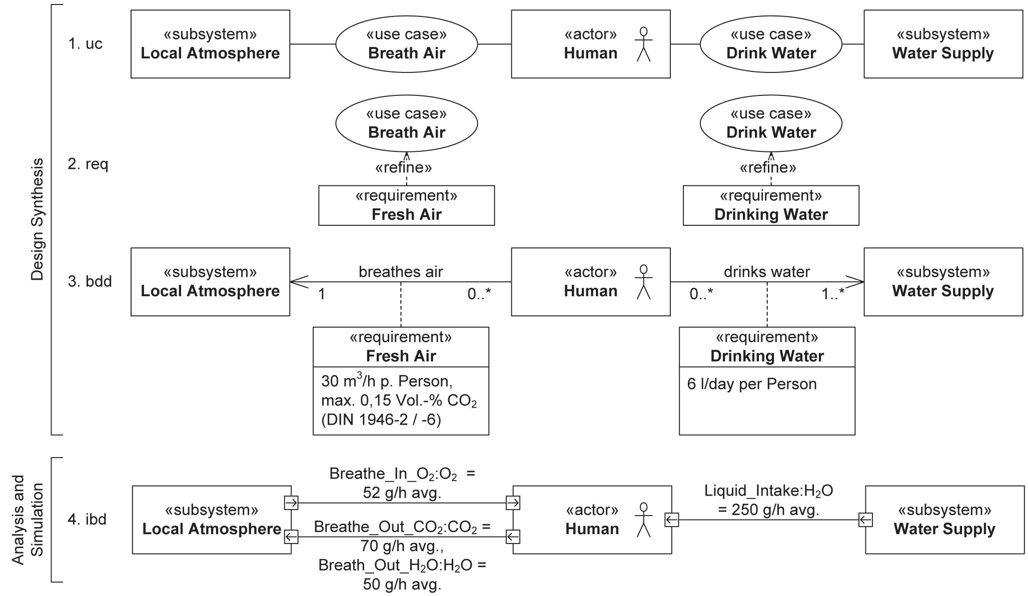


Figure 1
Besides the conventional systems view (4.), the illustration case shows a use case diagram (1.), a requirement diagram (2.), and a block definition diagram with requirements attached (3.). The third diagram type represents a requirement-driven functional modeling view of the system.

describes the actual flows with the direction of matters in an analysis-oriented way. In contrast, the diagrams of use cases (uc), requirements (req), and the modified block definition diagram (bdd) typically serve for design reasoning. In these diagrams, the direction of linking is design-oriented and provides a foundation for design synthesis. The association usually starts from the source of requirement and ends at the fulfilling component. As a consequence, the direction of the association (indicated by arrows that symbolize navigable links) points in some cases in the opposite direction of the matter flows, as e.g. in case of the liquid intake in Figure 1.

A Sustainable Building-Greenhouse-City System

For illustration of the method of PSM, a sustainable system of a building and its urban environment is outlined that features a productive greenhouse, a desiccant heating and cooling system, and a pyrolysis system. The diagrams developed in this section illustrate an innovative interaction structure that is self-sustaining in terms of water and biological matter and uses only renewable energy sources. The system design founds on research done by the Watergy research group [5], documented by Buchholz (2006). The central element of this research is a productive greenhouse that delivers energy, water, and food. The research of the Watergy Group includes two prototypes of such greenhouses. The first, built in Almeria (Spain), represents a closed greenhouse for sustainable food production with high performance and very low water consumption. The second prototype in Berlin (Germany) integrates a greenhouse for heating, water regeneration, and food production in a town house.

The focus in the following system development is set on the city-building interaction and the required energy and material flows. The system configuration aims at a decentralized sustainable food and water supply, the exclusive use of solar energy, and CO_2 absorption by pyrolysis. The resulting configuration for a sustainable city design is best suitable for arid regions where the water resources are very limited as it exhibits the following features:

- Closed water cycles: The configuration includes wastewater recycling by decentralized separation of wastewater into greywater, urine, faecal and biological waste. The first both were regenerated in the greenhouse; biological solid waste is recycled in the pyrolysis system.
- Closed material cycles: For the food production, local material flow cycles are outlined. The reuse of charcoal from pyrolysis for soil improvement also absorbs CO_2 and, thus, closes the gas's cycles.
- Renewable energy supply: For a sustainable supply with electricity, heating, and cooling energy, the system includes the technology of concentrated solar power (CSP) with attached generators for electricity as well as seasonal storing and transport of desiccants for heating and cooling purposes.

Use Cases and Requirements

The use case diagram (Figure 2) shows the most important functional subsystems of the city system. These consist in proving living and work space, a traffic system, and in energy, water, and food supply. The diagram assigns the essential use cases of the city system to its subsystems. The four subsystems and the use cases define an abstract framework that provides the context for the system to be designed.

The next level of the system description transforms the use cases to requirements. The requirements concretely describe the functions that the system and its subsystem need to fulfill. They define essential demands made on the design. The requirements in the sustainable city system concern four different types of item flows: energy, water, food, and area. Energy is needed as electric energy for transport in the city, for operating devices and lights, and as heating and cooling energy for providing conditioned living and working space. From the requirement of conditioned space, the need for an enclosed

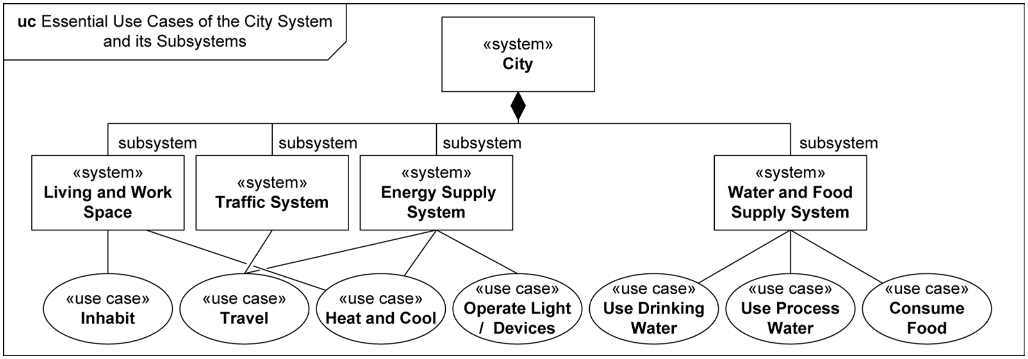


Figure 2
The use case diagram (uc) outlines how the inhabitant utilizes the system of building and city environment.

space derives, which is satisfied by the building. Furthermore, the water requirement splits up into two different types: drinking water and process water. This allows intelligent recycling and regeneration of water. The explanation of the system components attached by the «satisfy» relation (Fig. 3, bottom line) is part of the further development of the system design in the following section.

Requirement-Driven System Diagram and the Flow Diagram

The requirement diagram (Fig. 3) refines the use cases by attaching functional requirements. It does not contain any links between the components. For this step, i.e. the setup of a system of linked components, the block definition diagram (bdd) with associated requirements (Fig. 4) and the internal block diagram with item flow definitions (ibd, Fig. 5) serve. They represent two different views of the detailed system: a design-oriented view and an analysis-oriented view. The next paragraph explains the resulting system description by means of these both views.

An essential difference between the two views is that the design-oriented view (Fig. 4) includes the inhabitant as actor whereas the analysis-oriented view (Fig. 5) only contains the technical components

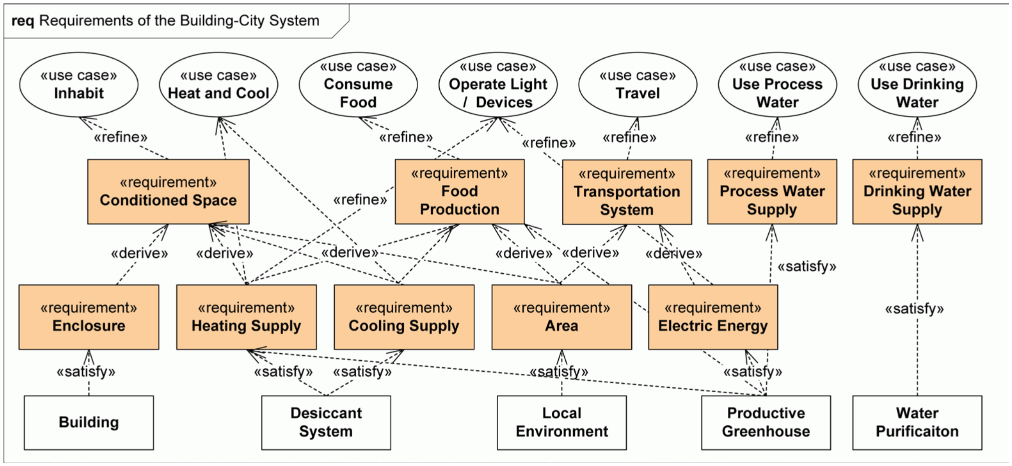


Figure 3
The requirement diagram (req) describes the desired functions of the building and its city environment.

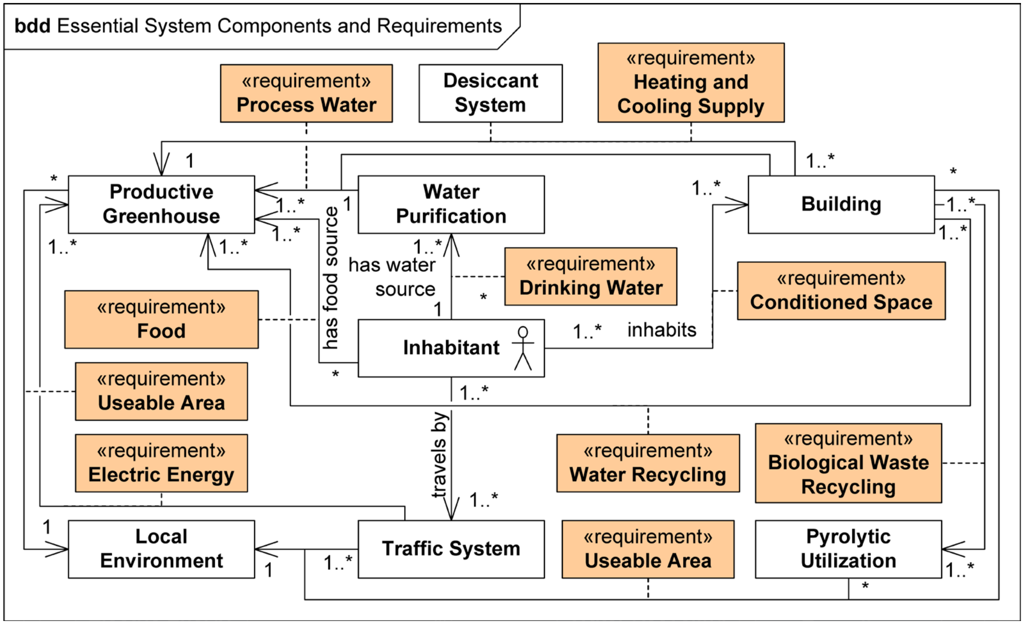
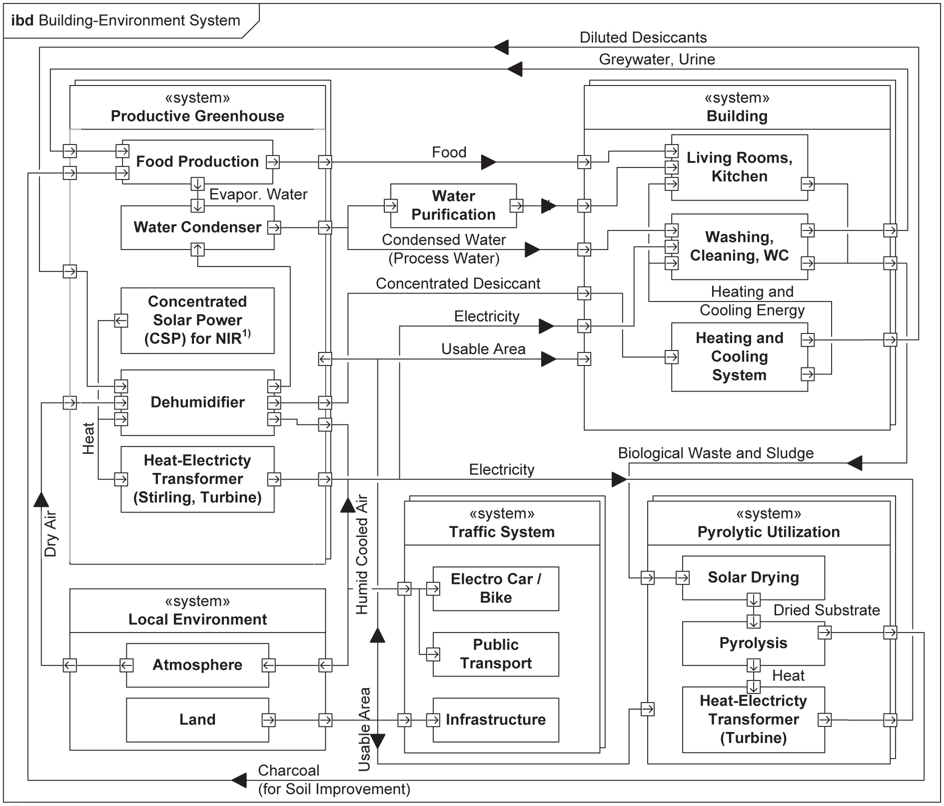


Figure 4
The block definition diagram (bdd) describes the system by design-oriented associations. Requirements attached to the associations leads to a requirement-driven view of the system.

of the city system. The productive greenhouse (Fig. 4 and 5, top left) is probably the most important component of the system. It provides process water, which is cleaned by the plants and is used for washing and cleaning processes. Furthermore, the greenhouse grows plants for food production with high effectiveness and integrates solar energy generation.

For energy generation, selective reflectors by Concentrated Solar Power (CSP) in the greenhouse concentrate the near-infrared and infrared radiation (NIR), which does not support the growth of the plants. The heat gained by this concentration serves, first, for producing electric energy by means of a gas turbine or a Stirling engine, and, second, for regeneration (drying) of the diluted desiccant with the waste heat at a lower temperature level. The second process stores energy by loading the desiccant (e.g. a brine) with hygroscopic potential. Within the building with its heating and cooling system, this potential serves to transport energy by forcing absorption leading to a process equivalent to a solar-driven heat pump. This heat pump provides heating and cooling energy for the building. The process of absorption has been examined for building heating (Buchholz et al., 2009). By absorbing humidity and transporting heat in this process, the desiccant solution is diluted and needs regeneration in the greenhouse. In the design-oriented diagram (Fig. 4), the desiccant system appears as association block. In the analysis diagram (Fig. 5), the desiccant system is distributed over other system parts. It appears in the greenhouse as dehumidifier, in the building as heating and cooling system, and in the item flows between building and greenhouse.

For process water gaining, a condenser integrated in the envelope of the greenhouse (Fig. 5, top left) collects water from evaporation processes of the plants and from the dehumidification process of the desiccant system. Note that the association of the process water between building and greenhouse (Fig. 4) points in the opposite direction as the flow of the process water (Fig. 5), since the design



[1)] NIR = Near Infrared Light

Figure 5 System structure as Internal Block Diagram (ibd) includes the main components of the sustainable-city system which are the building, productive green house, the traffic system, the pyrolytic utilization, and the local environment.

requirement origins from the building. For the requirement of drinking water, separate water purification is required. A further important feature of the water cycle is the separation of greywater and urine from solid biological waste. The liquid parts are recycled in the greenhouse whereas the solid parts undergo solar drying and pyrolysis, a process that produces heat and charcoal. The charcoal is used for soil improvement in the green house leading to a fertile soil called terra preta, in which CO_2 is absorbed. The Cycler Support Guide (Buchholz, 2008) describes the processes in more detail.

Conclusions

Parametric Systems Modeling (PSM) acts as a tool supporting performance-oriented and sustainable building and city design. The proposed method uses a component-oriented decomposition as supported by existing modeling standards such as IFC, CityGML, and gbXML. This decomposition type enables the designer to interact with the components of the design easily. This use of PSM allows to overcome the geometry-limited modeling approach currently practiced in building design and allows to embed links, analyses, and simulations. This continues of parameters the approach of Building Information

Modeling (BIM) and expands it to dynamic parametric modeling as it considers system dependencies and includs non-geometrical information. The design-oriented view represented by use case, requirement, and block diagrams is of special importance, since starting from requirements, tracing them, and switching forward and backward between the view of design reasoning and synthesis and that of matter flows, analysis, and simulation are essential activities of designing. Next steps for theoretically developing the approach further deal with the interaction and integration of the non-geometrical PSM model with the geometrical CAD model.

The application of the proposed method to a city-building-greenhouse interaction illustrated how this approach can serve as a tool for modeling innovative solutions with respect to non-geometrical properties. PSM allows the methodical design and proper integration of novel components, such as the productive greenhouse, the desiccant system, and the pyrolysis process, in the city-building system in order to achieve a sustainable configuration with closed matter cycles and with exclusive use of renewable energy. Especially, the Watergy greenhouse strongly relies on its system integration, as it serves for requirement satisfaction in different disciplines and exhibits an intensive interaction with the city environment. Thus, only a multidisciplinary view enables the designers to configure and dimension the resulting system correctly. For its future development, the innovative building-greenhouse-city system requires as next steps the further determination of parameters in detail, the adequate dimensioning of the requirements and flows in different environmental situations. The design-oriented and the analysis-oriented description by the SysML diagrams in this paper and their refinement support this work.

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