



## Systems modelling for sustainable building design

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### ABSTRACT

To support performance-oriented modelling for sustainable building design, one must both model geometric interdependencies in a parametric way and include non-geometric physical, environmental, and economic design reasoning. For this purpose, this paper examines the use of Systems Modelling Language (SysML) to model systems for sustainable building design and develops a method called Parametric Systems Modelling (PSM). Selected diagrams demonstrate the application of the method for performance-oriented building design and show generic models of typical requirements, design structures, internal processes, and item flows of energy and resources in a systems view. An exemplary implementation of a parametric system, which handles the trade-off between investments in both building envelope and heat generation technology, illustrates the use and benefit of systems modelling for decision-making. Further considerations address integrating systems modelling into the CAD/BIM-based design process.

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### 1. Introduction

Building energy consumption comprises approximately 40% of an industrial nation's total energy consumption [1–3] leading to the respective emissions. A recent EU directive defines ambitious goals for reducing energy consumption and greenhouse gas emissions and requires all buildings constructed in 2020 or later to be “nearly zero-energy buildings” [4]. This calls for performance-oriented building design, aiming to develop design configurations that have low resource consumption and emissions and that are economically feasible. To achieve significant improvement, one key is using the appropriate building modelling methods, considering the relevant engineering interdependencies, especially in early phases, to support the design process and the involved design experts. Sustainable building design requires considering the geometric and visual properties of the design as well as the physical, technical, and economic engineering interdependencies that determine the building's performance.

#### 1.1. Why we need systems modelling for sustainable building design

The current mainstream building design practice is predominated by methods that proceed sequentially in their disciplinary decision-making about energy and resources and that are segmented in the models used. Designers often develop conceptual designs, including building shape and appearance, without

considering energy and resource consumption. Furthermore, there is no direct link between energy simulation and design models, which leads to difficulties tracing the effects of changes. This results in probable interdependency neglecting and insufficiently exploiting the energy and resource efficiency potential.

For sustainable design, often called green building design, one must provide a holistic model because of the relevant criteria crossing disciplinary borders. Criteria catalogues that provide references for assessing building design sustainability, including the LEED Standard issued by the U.S. Green Building Council [5] or the handbook for office and administration building design issued by the German Sustainable Building Council (DGNB) [6], exemplify this multidisciplinary character. The main categories in the DGNB handbook, which serves as a reference in this paper, are ecological quality, economic quality, sociocultural and functional quality, technical quality, process quality, and site quality. The categories show the wide range of criteria and their disciplinary distributions. The interdependence of these criteria in the design object should be considered in designing a sustainable building and assessing its performance. A consideration of the multidisciplinary interdependencies in the design model is thus required to support sustainable design. Current building models insufficiently represent these architecture, engineering, and resource consumption interdependencies and focus on geometrical dependencies.

In addition to the current practice, research exists on including multidisciplinary interdependencies. This research is related to either multidisciplinary optimisation or design collaboration issues and discipline interaction in the design process.

Multidisciplinary optimisation requires a mathematical or algorithmic formal definition of the interdisciplinary

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interdependencies. Several optimisation studies cover interdependencies in this way. Grierson and Khajehpour [8] include cost and energy in office building design optimisation. Wang et al. [9,10], Rivard et al. [11] and Geyer [12] present optimisation studies that focus on architecture and green buildings, also considering energy and cost. Caldas [13], Shea et al. [14], Flager et al. [15], Welle et al. [16] and Geyer [17] also include daylight and, in part, view as criteria.

In contrast to optimisation, other approaches carry out research on discipline interaction in the design processes and its collaboration, which defines interdependencies neither mathematically nor algorithmically but relies on acting persons, agents, or other information flows. O'Brien et al. [18], Soibelman et al. [19] and Austin et al. [20] present typical experiments on computer-supported interpersonal design collaboration in student projects and professional workshops. Early research on collaboration in the design process, including Fischer and Froese [21] and Teicholz and Fischer [22] couple applications and start to develop integrated models, including products, processes, and organisational information for allowing a team discussion. Karola et al. [23] and Lee et al. [24] present similar approaches based on the Industry Foundation Classes (IFC) standard. Hegazy et al. [25] present an information model including design rationales. Khalfan and Anumba [26] and Anumba [27] examine implementing and adopting Concurrent Engineering (CE) and collaboration in the construction industry. More focussed on Multidisciplinary Design Optimisation, Bletzinger and Lähr [28] apply an agent framework for sensitivity analysis to support multidisciplinary collaboration. Garcia et al. [29] and Senescu et al. [30] present ontologies and methods to support and improve multidisciplinary collaboration.

Another research direction examines information flows and process-induced interdependencies. Austin et al. [35–37] structure interdependencies in constructional design and planning using Steward's Design Structure Matrix (DSM) [38] and a modified IDEF0 notation [45]. Karhu presents a similar generic method for modelling processes and construction schedules and applies it to precast facades [47,48]. Furthermore, based on the method of Steward, Eppinger et al. [49] and Eppinger [50] present a model-based approach for structuring design tasks and for using concurrent engineering in general engineering design. These approaches are limited to design and construction activities with information flows and do not include physical components with energy and resource flows in the system.

Some approaches link requirements with design. Gane and Haymaker [31] and Gane et al. [32] present an approach that combines collaboration and optimisation in a scenario-based design model, which includes elements of a requirement-driven parametric systems model in a non-standardised modelling language. Kamara and Anumba [33] represent a requirement reasoning approach to satisfy clients' demands. Kiviniemi et al. [34] present an approach that focuses on managing room programs as requirements for building product models and is related to the Industry Foundation Classes (IFCs); it thus shows the IFC capabilities in terms of requirements.

These approaches do not represent the architectural and engineering interdependencies of requirements and performance in a universal standard-based way to support the application of Systems Engineering. Models are either individually established for the specific case, which is usually practiced in optimisation studies and makes design integration difficult, or the models do not explicitly contain interdisciplinary dependencies, as they are part of the interpersonal interaction, which is not included in the model. To establish the required models for optimisation and collaboration, the approaches either use application conglomerations and their respective segregated models or software and individual model approaches not linked to standards and developed specifically for demonstration purposes. No approach provides a

standard-conforming description that includes relevant requirements and engineering interdependencies in design projects and crosses disciplinary boundaries, starting from early phases and continuing through the entire project, to provide a system model for sustainability engineering in building design.

Multidisciplinary interdependencies in the design object caused by the demand for energy efficiency and sustainability and the variety of possible solution configurations within these dependencies turn building design into a complex task. Therefore, the demand for sustainable solutions and the resulting engineering and architecture integration causes building engineering design to be a search for good solutions instead of just feasible ones. These issues lead to a new type of complexity that rarely occurred in building design in the past. Systems Engineering, with its respective modelling as an important focus, tackles this multidisciplinary complexity [7]. Applying Systems Engineering in building design thus promises a way to improve building performance substantially. Systems Engineering and the system model provide an explicit way to represent these interdependencies in the model to capture, discuss, and address them.

## 1.2. Adapting systems modelling for building design

The Systems Engineering approach, in which systems modelling has its origins, provides powerful tools to address complex engineering design tasks. The approach emerged in the context of designing large-scale systems in the second half of the twentieth century. Its methods were first applied to astronautics and aeronautics; they were later used for smaller systems with less design effort, e.g., in automotive or software design [7].

The development of modelling standards and languages played an important role in Systems Engineering. The Systems Modelling Language (SysML, first issued in 2007 by the Object Management Group, OMG, current Version 1.2, 2010) [53] represents the current terminus of this development. It is a universal modelling language for systems based on the Unified Modelling Language (UML) [56]. Weikens [54] and Friedenthal et al. [55] describe SysML and its application. Its predecessors include the Integration Definitions for Function Modelling (IDEF, issued between 1993 and 1995) [45], which contains the subordinate standards IDEF0–IDEF14 that address system-relevant aspects, including modelling functions, information, and processes. Other relevant systems modelling standards are the architecture frameworks of the British Ministry of Defence (MODAF, Version 1 in 2005) and the US Department of Defense (DoDAF, Version 1 in 2003). Starting in 2005, these frameworks were combined into the Unified Profile for DoDAF/MODAF (UPDM) [57], which OMG issued in its first version in 2007 (beta) and 2009 (final).

In contrast to other engineering design fields, systems modelling techniques are rarely present in building design. Parametric modelling, a technique representing parameter interdependencies between model components, which leading AEC software companies<sup>1</sup> have recently adopted, strongly focuses on geometry and fails to exploit the full potential of a discipline-integrative systems view. Many designers thus associate parametric modelling in AEC with ambitious geometries.

Recent developments in building modelling, currently subsumed under the term Building Information Modelling (BIM),<sup>2</sup> go beyond geometry definitions and are thus an important foundation

<sup>1</sup> The main players in the field of parametric and generative modeling are Bentley with Microstation and Generative Components (<http://www.bentley.com>), Gehry Technologies with Digital Project (<http://www.gehyrtechnologies.com>), which is derived from Dassault's Catia (<http://www.catia.com>), and Autodesk with AutoCAD Revit (<http://www.autodesk.com>).

<sup>2</sup> Eastman [43] provides an overview of BIM.

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