Integrated Design Process for Prefabricated Façade Modules with Embedded Distributed Service Systems

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Abstract. The awareness of the environmental impact of buildings concerning their CO₂ emissions, their energy and resource consumption has raised the challenges on building design, construction and operation. Building service systems are among the main contributors to building related emissions. Their consideration already in design is therefore of growing importance. Distributed service systems represent a new paradigm towards the supply of a building with energy and matter. Being small, efficient and networked, they can be distributed within the building fabric to allow an efficiently supply of the building space. Their employment, however, affects the spatial layout, construction and resulting building performance. In order to capture the resulting complex dependencies, a strategy to integrate such systems into the architectural design process is necessary.

In this work a design process is proposed, that integrates distributed service systems into building design, dissolving the classical divide between architectural design and service systems layout. Digital modelling and computational methods are employed to create and analyse design solutions, visualize performance criteria and provide the relevant data for the intended digital fabrication process. The process is exemplified using a joint university-industry case study project focusing on parametric façade modules, developed in a seamless digital process from concept to fabrication.

1. Introduction

The awareness of the environmental impact of buildings concerning their CO₂ emissions, their energy, resource and space consumption has raised the challenges
on building design, construction and operation. From the middle of the 19th century, the systems of building infrastructure for the supply of air, heat, electricity and information have influenced building design as well as performance [1]. Current efforts to reduce energy consumption and carbon emissions [2] have made them an increasingly important parameter of sustainable building concepts and designs.

Distributed service systems employ a novel paradigm to supply buildings with energy, mass and information. Their main characteristics are decentralization, miniaturization, integration and communication. For the supply of the whole building, a multitude of individual system units is networked, enabling the system to sensibly reacting to differing demands of the interior. Due to the small area to be supplied by the individual unit, the system components can be of small dimensions, requiring less space. Their small dimensions facilitate the integration into structural building components such as ceilings, floors, façade elements and walls [3] (Figure 1). In order to cooperatively supply their designated space they need to communicate and coordinate their actions.

Fig.1. Exemplary distributed building service systems (image by V. Ritter).
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This work describes an integrated design process that allows considering distributed service systems already in the early stages of an architectural design. It is described using a design case study, which was part of a joint university-industry research project.

2. Integrated design process

The following approach proposes a seamless digital process from the early, performance-based design stage to digital fabrication. The architect is supposed to take an extended role: by utilizing digital tools such as integrated performance assessment and simulation, the aim is to consider aspects of sustainability and related distributed building systems already during the design stage and to transfer this information to the fabrication stage.

The building chosen for the design case study is a four-storey office building near Zürich, Switzerland. The project developer wants to offer future users to choose from a variety of office configurations. These configurations provide different functional and spatial alternatives, ranging from classic single office to opens space office layouts. For the case study, a distributed supply air system is supposed to be integrated into wooden, prefabricated, façade modules. The modules will be fabricated using a computer controlled fabrication process and assembled at the building site.

2.1. Process Model

In architectural design, even though very much following a certain sequence of actions and states, specified process models or methods are oftentimes not considered [4]. In this approach, a generic process framework for the modelling of complex systems, the unified process [5], is utilized to structure the design process.
Originating in software development, it has been widely adopted and adapted by other industries facing similar challenges. Especially in the fields of systems engineering, the process is applied in industries such as aerospace and automotive for the development of complex, multidisciplinary systems [6, 7]. In the building industry, the process has applied to the design and development of technical infrastructure [8].

For the modelling of an integrated design process of distributed service systems, the unified process is adapted to fit the context of a building design and development. The process phases are chosen according to the life cycle of a technical system in a building and structured according to the modelling steps in the stages of concept and planning of the unified process (Figure 2): the definition of requirements, the analysis, the functional system design, the implementation and finally the validation of the design. The process follows a sequence of actions, which is shown in Figure 3. For the development and visualization of the generic design process, the Unified Modelling Language (UML) was used [9].
2.2. Requirements

The first step of the concept stage is the modelling of requirements. For a satisfying building design, the requirements to be met by a decentralized supply air system have to be clearly stated from the beginning on. Requirements can be defined as the conditions or capabilities a system must be able to conform to [9, 5]. They can be separated into functional and non-functional requirements.
2.2.1. Functional requirements

In order to be able to use buildings in accordance to their designed purpose, comfortable conditions of the indoor environment concerning air temperature and quality have to be achieved and maintained. For the building of the case study, most comfort criteria are defined by regulation. In this case the Swiss regulations SIA 180 and 380/1 [10] apply, outlining comfortable interior conditions for office buildings (Table 1).

Table 1. Comfort regulations for office buildings, according to SIA.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor temperature (winter / summer)</td>
<td>19-26°C</td>
<td>Heating</td>
</tr>
<tr>
<td>Radiation asymmetry (winter, cold walls)</td>
<td>&lt; 10 K</td>
<td>Heating</td>
</tr>
<tr>
<td>Air exchange rate (office)</td>
<td>15m3/h x p</td>
<td>Supply air</td>
</tr>
<tr>
<td>CO₂</td>
<td>&lt; 1500 ppm</td>
<td>Waste air disposal</td>
</tr>
<tr>
<td>Air speed (winter)</td>
<td>&lt; 0.15 m/s</td>
<td>Supply / waste air</td>
</tr>
<tr>
<td>Humidity (winter)</td>
<td>30%-50%</td>
<td>Supply / waste air</td>
</tr>
</tbody>
</table>

2.2.2. Non-functional requirements

An important non-functional requirement in particular for the case study is the flexibility of partitioning and re-partitioning of the office space. If considered in the design stage, distributed service systems allow a more flexible supply of different spatial layouts by allowing different aggregations of components to supply different spatial entities. A non-functional requirement is also the minimization of transport energy required to supply the designated space.

3. Demand Design and Performance Assessment

In order to layout and configure the distributed service systems, the demand of energy and mass of the specific building design has to be assessed. This is an integral part of the design process as design decisions on form, material and technical systems are interrelated concerning the overall building performance (Figure 3). For performance assessment, more information than just the geometry is necessary. A building information model (BIM) is used from the beginning of the design to model and capture multidisciplinary information [11]. Using a BIM, all necessary structural, functional and technical building elements including their
geometrical, topological and semantic information can be established in a short amount of time.

The Design Performance Viewer (DPV) [12] is a software tool developed for integrated building performance assessment (Figure 4). It is directly embedded into the BIM modelling environment, in this case Autodesk Revit [13]. No export or import of data is necessary, thus reducing potential data loss or misinterpretation. At the time of the case study, the DPV employed the energy calculation model of the Swiss norm SIA 380.1. The DPV searches the BIM for available information, which then is used to run the monthly-based energy simulation and visualize the results.

![Case study building information model, DPV interfaces.](image)

Room objects in the BIM represent the functional building space, containing the necessary information of occupancy, equipment and air exchange rates. A room object is bounded by wall, ceiling or floor objects which face either to the outside or the inside environment. These objects are equipped with material parameters such as u-values. Openings such as windows are equipped with parameters of orientation, u-values and g-values. The DPV evaluates and aggregates energy gains such as solar or internal gains and losses such as transmission and ventilation heat losses to deliver the energy balance for every room object and, resulting, the entire building. By storing all necessary parameters, their values as well as all object-, and building-related calculation results directly in the building information model, the model can be easily exchanged between participants of the collaborative design process.
4. Supply design

For the research project and case study, a distributed supply air system (Figure 1) was chosen as the exemplary system to be embedded. The supply air is taken directly from the outside through perforations of the building envelope. The air is filtered, tempered and distributed either directly into the room or into a networked duct mesh to supply spaces deeper inside the building. Due to its small sizes, the system components can be integrated into structural building elements such as floors, ceiling and façades. For the case study, the prefabricated façade elements and floors were chosen to host the system components.

4.1. System components

A distributed supply air system is defined by transport, effect, inlet and outlet components. These components are connected to establish the supply air network. The most important component of the system is the transport component. It combines the transport of the supply air and its conditioning, taking either fresh supply air or the existing interior air. Each component contains four pc-size fans to establish an airflow rate up to 100m³/h. The heat exchanger uses hot or cold water to temper the supply air before emitting it into the room. Each unit can be controlled individually or cooperatively, resulting in a highly flexible and individual supply. The unit can be integrated in to floors, ceilings and facades using an installation casing, which allows later access for maintenance. The supply design phase aims at a system layout that is capable to meet the requirements. The type and amount of necessary system components and connections are derived from the requirements combined with available building information from the BIM.

4.2. System topologies

The next design step is the contextual placement of the components and the layout of connections to establish the distributed supply air system. A distributed supply air system employs air, water and electricity to deliver heat and cold. For each medium, a suitable topology has to be applied.

4.2.1. Component locations

The placement of components is constrained by the functional aspects such as connectivity of components as well as contextual parameters such as building construction, partitions, usage and flexibility of the spatial entities. The placement of components follows a bottom-up process, starting at the visible parts of the system, the system inlet and outlet. Outlet components influence the interior design of a room. Their placement follows functional criteria such as radius of
emission but also aesthetic criteria. As airflow is also constrained by room boundaries such as walls, the configuration of the space also influences the number and placement of outlets. A perforation of the building envelope is necessary to access the supply air from the building environment. The type and position of inlet components are defined by the construction and design of the building envelope. Depending on the façade type, material and the design intent, inlet components can greatly influence the aesthetics of the façade. For the case study building, the transport components are to be placed in the façade. The façades of the case study building allow placement of the components only in opaque façade elements. Elements containing a window do not allow placement as the chosen window type spans from floor to ceiling. After defining the amount of components in the functional design stage, the components are placed in following steps (Figure 5). Based on the initial model (step 1), possible locations for the components are evaluated according to the design constraints (step 2). First, the outlet components are placed in the marked floor areas. Their location can be chosen following different design criteria such as distribution radius or aesthetics. Afterwards, the transport/effect components together with the inlet component are placed according to their designated locations (step 3). After the functional design and their placement, the components have to be connected to establish the system (step 4).

Fig. 5. Steps (1-4) of component locations, placement and connection.

In the case of distributed air supply, a connection to each of the three medias, air, water and power is necessary. Based on the characteristics of the medium, different network topologies apply. For the distribution of the supply air as the central medium, only partially connected mesh network topologies are considered. This topology allows the transport of supply air from the inlet into the
building depth. A meshed network allows an even pressure distribution, supplying a varying amount of outlet nodes. In the case of façade inlets, outside air pressure differences on the facades on windy days can be utilized to support the distribution of the supply air, to pressurize the air network [14]. Additionally, the redundancy of the system is higher than using a hierarchical tree topology as each outlet is connected to at least two supply ducts. A fully connected mesh network topology, where each node is connected to every other node, is economically not feasible, nor could it be integrated into structural components.

![Image](image.png)

*Fig. 6. 2D/3D Representation of components and networks in the BIM.*

5. Implementation

The implementation stage addresses the physical placement of the system components. By employing a building information model as a three-dimensional representation of the building, possible locations for system components can be identified more easily. After the functional design, the placement of components and the establishment of topologies, the systems are now represented in their actual geometry. The realization of integrated façade elements containing distributed service systems is constrained by the chosen building construction, facade materiality, floor height and façade opening sizes.

For the modelling of the case study building and the integration of distributed service systems into the building information model the software Autodesk Revit [13] was used. All system components were modelled as parametric objects and placed in the building model (Figure 6). For the detailing of the construction and the digital fabrication of the integrated façade elements, their dimensions, locations and connectivity have to be part of the model.
The modelling software used for the case study provides an export of the proprietary building information model as a generic IFC (Industry Foundation Classes) [15] model. This includes all necessary building data, including the system component objects. Using the IFC standard enables the identification and the propagation of building and systems information throughout the process. The IFC contain a HVAC domain providing a large set of HVAC entities and a generic approach for modelling HVAC components [16]. Some components of the distributed air supply system such as the outlets can therefore be described using different standard objects. These standard IFC definitions can be dynamically extended by adding custom property sets (Pset), describing the individual component parameters [16]. By combining standard IFC entities with custom property sets, object and system information of distributed service systems can be exchanged between the different disciplines, in this case from the design environment to the engineering and the fabrication environment. This allows reviewing the building information model for functional or geometric inconsistencies as well as for possible clashes between system components and building structure. The extended IFC model is then passed on to the software facilitating the detailing of the construction and the automated fabrication of the integrated façade elements on computer numerically controlled machinery (CNC).

6. Systems validation and optimization

After the functional design, the definition of topologies and placement of systems in the building geometry, the validation and refinement of the system design is possible, addressing functional and non-functional system requirements as defined at the beginning. Refinement aims at improving the system performance by changing type, location or connections of components in order to achieve a more efficient operation.

6.1. Network pressure distribution and airflow

The system has to be able to achieve and maintain the comfort requirements named above. This is to be achieved most efficiently, demanding an even distribution of air using a minimal amount of transport energy. For validation and refinement purposes, a steady state calculation model of mass and energy conservation principles for compressible flows is employed [14]. The network is described in different types of nodes, which can either be transport nodes or outlet nodes. Ducts connect the nodes, forming different variations of partially connected meshes. For each instance of the mesh, the pressure distribution and airflow rate at every node is calculated (Figure 7).
Fig. 7. Network setup, initial topology (top: subsystem 1,2,3 left to right), calculated airflow (bottom).

The network is described in XML; this input can be generated based on the building information model equipped with the system components: Each component representation contains the necessary information of its location (x, y), its semantic information (pump, opening) and its connectivity (node1, node2). Strength and direction of the airflow within the network is calculated and visualized by weighted lines and arrows. In addition, the amount of air emitted at the outlet node is calculated and visualized (Figure 7). For optimization purposes, different network topologies obtained from the BIM can be calculated and evaluated. In a further step, methods of Computational Intelligence such as multi-objective genetic algorithms as well as routing algorithms can be employed for an automated search for the optimal layout.
7. Digital fabrication

Over the past years, techniques of digital fabrication have contributed to the formal repertoire of architecture [17]. The rise of digital modelling in design has strongly supported this development, also resulting in comprehensive file formats for data exchange. For the case study, the IFC are used to transfer the exact geometry of the façade elements to specialized applications and tools for digital wood fabrication. The abstract geometry established during the design stage is then further detailed using the exact material definitions and wood construction types. Manufacturing parameters such as coordinates for automated nailing and glue application are added. The manufacturing model can be used for direct fabrication using CNC fabrication machinery (Figure 8). For the system components and networks of the distributed supply air systems, necessary niches and openings are included.

![Digital fabrication of façade element, integrated system components](image_url)

*Fig. 8. Digital fabrication of façade element, integrated system components [18].*

8. Discussion and conclusion

The case study describes the application of a fully digital process for the collaborative design of parametric façade elements, including the integration of distributed service systems from the beginning of a design. A building information model is used as the database to create and exchange the necessary information among project participants. The BIM is also used for instantaneous analysis and visualization of flows of energy and mass to allow the architect and designer to consider building performance, resulting distributed systems and components and thus to take better-informed design decisions.
A. SCHLUETER

The objective for the participating fabrication firms was to obtain better digital design data from the architects to reduce their efforts in reproducing and manually processing the design data for fabrication purposes. In a conventional design setting, the façade would have been designed by the architect using a CAD environment. The 2D design documents would have been passed to the engineer, who would filter, add and partially recreate the information necessary for performance assessment and technical systems layout. The documents would then be passed to the fabrication company to be re-entered in three dimensions, including fabrication parameters, to be fabricated on CNC machinery. Even though this was not measured and compared within the project, the experience from project participants leads to the conclusion that the one-directionality, the multiple inputs of the same information and the manual adjustments make a conventional process tedious and error-prone.

The presented approach fundamentally changes this process by utilizing a seamless digital workflow. For the façade element geometry, including the embedded distributed service systems, this is achieved by using IFC for object definition and exchange. By customizing IFC objects, additional fabrication information can additionally be added already when the representing objects are created in the building information modelling editor. Vice versa, architects can consider fabrication possibilities and constraints, even use them as design drivers. The research was geared at proof of concept and thus quite pragmatic, using existing proprietary software, extending it to the desired functionality and using an enhanced IFC export and import functionality. This of course does not guarantee the applicability of this process to every possible combination of software tools. However, the case study leads to the conclusion that the presented digital design process has significant potential to improve the design-to-build process for integrated façade elements.

9. Acknowledgements

The case study was conducted in context of the research project Integrated Parametric Façade Modules (IPFM). Participants and contributors to the research project were:

• Chair of CAAD, ITA, Department of Architecture, ETH Zürich (lead)
• Chair of Building Systems, ITA, Department of Architecture, ETH Zürich
• Institut für 4D-Technologien, Fachhochschule Nordwestschweiz
• Façade Competence Center, Lucerne University of Applied Sciences and Arts
• ERNE AG
• Aeppli Metallbau AG
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- BS2 AG
- Halter AG

References