Abstract

In this research a graph-based methodology has been developed to support modular building design. A graph-theoretic algorithm is used to decompose the design into modules that facilitate the future replacement of building components, allowing buildings to be more easily adapted to changing user requirements. The future flexibility of the building is increased by decomposing it into custom-designed modules, containing adjacent components that currently belong to different systems, but need to be replaced at the same time in the future. The reduction and standardization of the interfaces between the modules can also reduce the interdependencies between the activities for installing the building components, which are currently carried out by different subcontractors. It is shown that this approach to modularization increases the flexibility of the design, as well as reducing expected time overruns during project execution. Such overruns normally occur due to the knock-on effects of a delay in one construction activity on other interrelated activities that are carried out by different subcontractors. The methodology is demonstrated through a case study of a residential housing unit.

Keywords: Automation; Design Management; Modular Construction

1. Introduction

A Work Breakdown Structure (WBS) is commonly used in the planning of construction projects, in order to systematically break down processes into individual activities. The WBS can serve as an effective tool to identify and manage the interfaces between activities carried out by different teams or organizations (Chua and Godinot 2006). However, the WBS is currently often not sufficiently differentiated from the Product Breakdown Structure (PBS) (Lamers 2002). The PBS is based on a decomposition of the building into distinct systems and components, and the consequent division of labor between the different design consultants. Each of these components satisfies certain performance requirements. But such a decomposition of the design is based on the project's user requirements, not on those of the construction and renovation processes. When the WBS is merely regarded as an ersatz-PBS, the numerous and poorly managed interfaces between different activities, many of which are a result of physical connections between the components constructed in these activities, exacerbate project overruns. A delay in one activity immediately has knock-on effects that cause additional delays in other activities. The fact that interrelated activities are often carried out by different subcontractors increases this problem, as each subcontractor seeks to optimize the allocation of his resources among a number of projects he simultaneously carries out, and is less concerned with the effect that delays in his activities have on other subcontractors in the same project.

One solution to this problem is to use buffers in project planning. However, buffers generally involve the allocation of additional resources, such as time and manpower, which carry a cost. An additional solution, which this study seeks to explore, is to modularize the design of a building. As will be demonstrated, modularization can reduce the interdependencies between activities carried out by different subcontractors. The term modularization is used here to refer to custom designed assemblies of components, which have standardized interfaces with other assemblies. Such custom-designed modules diverge from the classical approach to modularization in construction, which seeks to divide the building into identical repetitive units. The standardization of the interfaces between modules, rather than the modules themselves, puts fewer constraints on the design, and makes it easier to accommodate the user's requirements for the performance of the project.

In order to take into account the entire life cycle of a building, modularization should also accommodate the future renovation and adaptation of buildings to varying user needs. Increasing the adaptability of buildings is one of the most effective ways to increase their value, and their users' satisfaction (Manewa, Pasquire, Gibb, & Schmidt, 2009). In practice, most buildings are, however, designed and constructed to suit their use at that time,
and their future adaptability is ignored (Beadle, Gibb, Austin, Fuster, & Madden, 2008). As a consequence, components with different replacement rates are currently often physically and functionally connected to each other, with the result that minor changes require the demolition and replacement of many components. The hypothesis of the present research is that modularization can increase the adaptability of buildings through the systematic separation of building components whose replacement occurs at different intervals in the future.

In this study, a methodology has been developed to support a modularization of building design. Such a modularization would follow the preparation of an initial design, and precede the detailed planning of the construction (Figure 1). It is assumed that the modularized design would better serve the requirements of the construction and renovation processes. The design is decomposed into distinct modules, each of which contains several components that may belong to different building systems, but have the same replacement rates. The application of such an approach is particularly challenging in the design of large buildings, which contain thousands of different components that are interconnected through various types of relationships. Consequently, the present research focuses on the development of a semi-automated methodology that can support the definition of such modules. The methodology enables the functional and geometric coordination of the design of the modules.

Figure 1. The proposed modularization phase, within the construction process

2. Methodology

The separation of building parts to allow adaptability has been studied in previous research. In Open Building systems, the ‘base-building’ and its interior are separated (Habraken, 2003). Most of the previous research has focused on the separation of entire building systems (Hansen & Olsson, 2011; Leupen, 2006). Durmisevic and Brouwer (2002) have proposed to extend this approach in order to include the separation not only of entire building systems, but also of individual components within a system, which may have different replacement rates. Following a similar approach, the modularization of the design is supported in the present research through a methodology composed of the following steps:

1. Representation of the building design and project requirements as a graph
2. Ordering the components according to their relative replacement rates
3. Implementation of a clustering algorithm to identify the optimal modularization
4. Verification of the adaptability of the design by calculating the betweenness centrality of the components.

1.1. Graph-based representation

The proposed methodology is based on the use of graphs to represent the design of building components. This information is extracted in IFC format from a Building Information Modeling (BIM) database, in which building components are represented as objects (Bock and Isaac 2013). It is then translated automatically into a graph-based model in which a set of nodes $v \in V$ represents the components in the design, and a set of links $(i,j) \in A$ represent physical connections between these components (e.g. when one component is covered by another component).

1.2. Ordering of the components

Components are ordered according to an initial assessment of their replacement rates, in order to define modules that contain components with the same replacement rates. The replacement rates $r_i$ are stored in a generic database, and are based on pair-wise comparisons by experts, rather than on an assessment of the actual size of the life expectancies of the systems. It may be clear, for example, that the building structure is likely to last longer than engineering services components, and that some of these components will last longer than finishes and fittings, but it can be very difficult to determine the exact number of years they will last. It is therefore more feasible to use an order topology for such an assessment, instead of a metric topology. In other words, it is possible to assess which component is likely to be replaced sooner, even when it is difficult to assess
when exactly this will happen. In addition to allowing the assessment of relative, rather than actual replacement rates, pair-wise comparisons have the advantage of being transitive, i.e.:

\[ r_i > r_j \text{ and } r_j > r_k, \text{ then } r_i > r_k. \]

Ordering the components in this way enables taking into account their technological and economic lifecycles.

1.3. Implementation of a clustering algorithm

Graph-theoretic measures of topology facilitate an identification of the optimal modularization of the design, in light of the physical connections between components and their expected replacement rates. Specifically, a clustering algorithm is applied to identify groups of components that are connected and have similar replacement rates.

The assessed relative replacement rates \( r_i \) are defined as attributes of the building components (Figure 4). A weight \( a_{ij} \) is added to link \((i,j)\) to represent the difference between the relative replacement rates of components \(i\) and \(j\):

\[ a_{ij} = \left(1 + |r_i - r_j|\right)^{-1}. \]

Here \( a_{ij} \) is an entry in the adjacency matrix \( A \) of the graph, which is symmetrical (i.e. \( a_{ij} = a_{ji} \)).

A hierarchical clustering algorithm, based on lambda sets, is applied to identify clusters of nodes in the graph-based model. The link connectivity \( \lambda(a,b) \) of a pair of nodes \( a \) and \( b \) is the minimum number of links that must be deleted so that there is no path connecting them. A lambda set is a maximal cluster of nodes \( S \) with the property that the link connectivity of any nodes within the cluster \( a, b, c \in S \) is larger than the link connectivity of any pair of nodes, one of which is in the cluster and one of which is outside (Borgatti et al. 1990):

\[ \lambda(a,b) > \lambda(c,d). \]

Thus, we expect the components within a module to share more connections than components belonging to different modules. When \( \lambda \) is large, the lambda set describes an assembly of components that are relatively difficult to disconnect from each other. These should be components which are installed onsite by the same team, and are unlikely to be replaced at different intervals in the future. Such a strategy can also enable the future disassembly of modules in order to upgrade and reassemble them, thus prolonging their sustainable life cycle.

A software called Visone was used to apply the clustering algorithm (Baur 2008). Visone was originally developed for the analysis and visualization of social networks, but was found to be useful in the present research for the analysis of construction projects as well. The two-step clustering algorithm employed first computes the link connectivity between all pairs of nodes. In the second step, the algorithm uses this information to construct the lambda sets.
1.4. Verification by calculating betweenness centrality

The clustering algorithm is used to support decisions regarding the modularization of the building design, in order to increase the constructability and adaptability of this design. These findings are verified by comparing the assessed replacement rates $r_l$ of individual components with the betweenness centrality $g(i)$ of corresponding nodes in the graph. The betweenness centrality $g(i)$ indicates the importance of a node $i$ in the organization of flows in the network, defined as the fraction all shortest paths between nodes in the network that pass through $i$:

$$
g(i) = \sum_{a \neq i \neq b} \frac{\sigma(a,b|i)}{\sigma(a,b)}
$$

where $\sigma(a,b)$ is the number of shortest paths between nodes $a$ and $b$, and $\sigma(a,b|i)$ the number of those paths containing $i$ as an inner node.

The correlation between the replacement rate $r_l$ and the betweenness centrality $g(i)$ should be negative. If the relationship is positive, this either implies that the replacement rates of these components are not low enough, or that they connect too large a number of other components. In the first case, the replacement rates of these components can be reduced through the use of buffers in the design. Such buffers are applied by designing components with a capacity larger than that required in order to fulfill the present user requirements in the building program. This extra capacity can be used in the future to absorb the impact of changes in user requirements, without requiring a change in the components. In the second case, relationships can be reduced through modularization, and the introduction of easily disconnected interfaces.

3. Case study

The proposed methodology was implemented in a case study of a typical housing unit, containing components such as interior partition walls, HVAC ducts and electricity piping (Figure 3a). To implement the methodology, a BIM model in ifcXML format was automatically translated into a graph representation in GraphML format. The links in the graph were weighted according to the assessed replacement rates of the components. For this, the components were divided into 3 groups with different relative replacement rates: 1) Structural and building envelope components; 2) Main ducts and pipes of the M&E systems; 3) Partition walls, and local ducts and pipes.

A clustering algorithm was then executed in the Visone software, and a number of clusters identified as potential modules. These included assemblies of components belonging to different M&E systems, as well as partition walls and the pipes they contain. Following the identification of these potential modules, the design could be adjusted, for example by replacing existing partition walls with a Robotic Service Wall that was developed in another funded research project – “Living Independently In South Tyrol Alto Adige” (Figure 3b) (Linner, Georgoulas, & Bock, 2012). This wall can be custom designed according to various configurations, and can be easily installed in any residence without requiring specific space dimensions. The choice of modules was verified by comparing the assessed replacement rates of the components in the modules, with their betweenness centrality. As expected, those partition walls that were identified in the clustering algorithm displayed a high betweenness centrality, yet also had a high replacement rate. This confirmed that the changes that were likely to be required in the future for these walls would also affect many other components, unless a strategy of modularization was implemented.
The impact that the modularization would have on the duration of the initial construction process was also assessed, through a Monte-Carlo simulation of the sequence of activities required to install the different components in the housing unit (Figure 4). The assessment of the durations of the individual activities in which the modules would be installed was very conservative. In fact, these durations were defined as being identical to the durations of the activities for installing the components in the original design – while in practice it is highly likely that they would be much shorter, due to the relative ease of installing a small number of modules with standardized interfaces. Despite this, the simulated duration of the entire construction process was found to be shorter for the modularized design, with a 90% probability that it would take up to 16 days. This, in contrast to a 90% probability for a duration of up to 19 days for the construction process according to the original design. Since the durations of individual activities were assessed to be identical in both versions, this change can be entirely attributed to the reduction of interfaces between activities carried out by different subcontractors, when modules are introduced.

Figure 4: Simulated duration of construction process according to the original design and the modularized design.
4. Conclusions

The design of buildings can have a major impact on the way they are constructed and renovated. Changing the design of a building can improve its constructability and the efficiency of construction processes, and enable future physical changes to be made in the building with greater ease, in accordance with changing user needs. The design of a building should therefore take into account its entire lifecycle, including onsite construction and renovation activities. In the present research, a graph-based methodology has been developed to support a modularization of the design that would better serve the requirements of the construction and renovation processes. The implementation of the methodology in a case-study demonstrates that modularization can ensure a more distributed construction plan, replacing the tightly coupled structure of current construction plans.

References

Baur, M. (2008). Visone - Software for the Analysis and Visualization of Social Networks, Ph.D., Fakultat fur Informatik, Universitat Fridericana.
Beadle, K., Gibb, A., Austin, S., Fuster, A., & Madden, P. (2008). Adaptable Futures: Setting the Agenda. Paper presented at the 1st International Conference on Industrialised, Integrated, Intelligent Construction, Loughborough, UK.
Bock, T. and Isaac, S. (2013). A methodology for adapting housing stock using modular infills, Paper presented at the Creative Construction Conference 2013, Budapest, Hungary.
Borgatti, S.P., Everett, M.G., and Shirey, P.R. (1990). "LS sets, lambda sets and other cohesive subsets." Social Networks 12(4), 337-357.
Durmusevic, E., & Brouwer, J. (2002). Design Aspects of Decomposable Building Structures. Paper presented at the the CIB Task Group 39, Design for Deconstruction and Materials Reuse, Karlsruhe, Germany.
Habraken, N. J. (2003). Open Building as a condition for industrial construction. Paper presented at the 20th International Symposium on Automation and Robotics in Construction, Eindhoven, the Netherlands.
Hansen, G. K., & Olsson, N. O. E. (2011). Layered Project–Layered Process: Lean Thinking and Flexible Solutions. Architectural Engineering and Design Management, 7(2), 70-84.
Lamers, M. (2002). Do you manage a project, or what? A reply to “Do you manage work, deliverables or resources”, International Journal of Project Management 20(4), 325-329.
Linner, T., Georgoulas, C., & Bock, T. (2012). Advanced building engineering: Deploying mechatronics and robotics in architecture. Gerontechnology, 11(2), 380.
Manewa, A., Pasquire, C., Gibb, A., & Schmidt, R. (2009). Towards Economic Sustainability through Adaptable Buildings. Paper presented at the The 3rd CIB Conference on Smart and Sustainable Environments, Delft, Netherlands.