Axiomatic Design and Design Structure Matrix for Circular Building Design

Marianna Marchesi(✉)

Welsh School of Architecture, Cardiff University, Cardiff CF10 3NB, UK
marchesim@cardiff.ac.uk

Abstract. The study aims to propose the integration of Axiomatic Design (AD) and Design Structure Matrix (DSM) methods to support the implementation of building reversibility within circular building design (CBD). In CBD, strategies for building reversibility have been formulated, but available tools mainly support design evaluation in the late stages. On the other side, in engineering design, methods to support reversibility in early design stages are available. AD and DSM are two matrix-based product modelling methods that are used in the analysis and modelling of relations in complex systems from the concept design. AD guides the designers in modelling the relationships between functional elements and physical components in a structured manner from the early design stages. DSM provides a method for modelling physical relationships among the physical components and groups them into modules. Despite the potential benefits of using these matrix-based design methods, previous studies on building reversibility within CBD have not yet explored this proposition. The study intends to place the theoretical premises for the application of AD combined with DSM within CBD for building reversibility. The study applies theory-oriented research by exploring, collecting, and evaluating relevant information from different theoretical and practical sources to formulate propositions on building reversibility within CBD. Propositions will be tested in future real-world applications while detecting challenges and limitations to assess effectiveness in supporting building reversibility within CBD.

Keywords: circular building · building reversibility · matrix-based product modelling methods · Axiomatic Design · Design Structure Matrix

1 Introduction

Circular building design (CBD) has recently achieved interest and recognition because of its potential for sustainable development in the built environment through the application of the circular economy approach to building systems, components and materials. Within CBD, building reversibility concepts and design strategies have been formulated to support the implementation of circular building solutions. However, this theoretical content is not yet fully embedded within design frameworks and tools to support the design process. The lack of design tools for the development of circular buildings through design strongly limits the application of circular strategies in the building sector [1].

V. Ungureanu et al. (Eds.): CESARE 2024, LNCE 489, pp. 424–435, 2024.
https://doi.org/10.1007/978-3-031-57800-7_39

On the other side, in engineering design, methods to support product reversibility in early design stages are available. AD and DSM are two matrix-based product modelling methods increasingly being used for reversibility in complex systems through modelling relations since the concept design stage [2].

The study aimed to define the theoretical propositions to support building reversibility within CBD by combining AD and DSM. Despite the potential benefits of matrix-based product modelling methods, previous studies have not yet considered the proposition of combining AD and DSM for building reversibility within CBD. Thus, the objective of this study was to provide theoretical premises on the application of AD-DSM to support building reversibility within CBD.

The research questions were the following:

1. What is building reversibility within CBD?
2. How is building reversibility supported by design tools within CBD?
3. Can AD-DSM methodology support building reversibility within CBD?

The research objectives were defined as reported below:

1. define building reversibility within CBD and how to implement it in design by a literature review.
2. analyze and compare existing design tools within CBD to support building reversibility and define existing gaps.
3. analyze AD-DSM theory to show potential to fill gaps in building reversibility within CBD and define propositions to be tested in future by applications.

The study consisted of theory-oriented research aiming at contributing to theory development by exploring design methods that can support the implementation of building reversibility within CBD. The study was conducted through exploration by collecting and evaluating relevant information from different theoretical and practical sources to formulate propositions and assess how exactly they could best contribute to CBD. This information came from different sources concerning the object of study (insights from existing research, and the researcher's experiences). This theory-oriented research started with an exploration of theory and practice to find available propositions regarding building reversibility within CBD. Relevant propositions were finally formulated for being tested in future research to show evidence of their relevance, define challenges and limitations, and potentially advance the theory in CBD.

The paper is structured as follows. Section 1 provides definitions for building reversibility in a circular building, related design frameworks, their comparison for integration and the analysis of available design tools for building reversibility within CBD. Section 2 provides an introduction to matrix-based product modelling methods and an overview of AD and DSM and their combination for building reversibility in CBD. Finally, Sect. 3 formulates propositions for future research and conclusions.

2 Building Reversibility Within Circular Building Design

2.1 Concepts and Design Frameworks

A circular building is "a building that is developed, used and reused without unnecessary resource depletion, environmental pollution and ecosystem degradation. It is constructed in an economically responsible way and contributes to the well-being of people and the biosphere. Here and there, now and later. Technical elements are demountable and reusable at the end of their (extended) lifespan, and biological elements can also be brought back into the biological cycle" [3].

CBD supports the design of circular buildings. The Circular Buildings Toolkit [4] is one of the design frameworks available to support the design of circular buildings. It provides a set of objectives and targets to point out and assess circular buildings. This framework is different from others since it arranges design strategies along the design process from the design brief to the manufacturing and construction according to the RIBA plan of work [5] to support the design team and key stakeholders in the implementation of circular buildings. The RIBA Work Plan is a process model for building design, construction and use. This model does not include the recovery stage.

Within CBD, building reversibility is the ability of a building to be easily adaptable during its use to guarantee high transformation potential and to be easily disassembled at the end of its service life to guarantee high reuse potential. Building reversibility provides systems, components and materials with the capability to be adapted and dismantled without damaging surrounding parts to support the potential for transformation or reuse in other contexts [6]. Building reversibility is achieved by combining reuse, adaptability and disassembly strategies. Three dimensions of building reversibility are distinguished: (1) spatial reversibility to adapt spaces; (2) technical reversibility of systems to reconfigure/upgrade systems; (3) technical reversibility of elements to separate elements and materials [5]. The Reversible Building Protocol (Table 1) is a design framework developed to address building reversibility.

Spatial reversibility is defined as the capacity of a building space to accommodate different functions by allowing transformation from one use scenario to another without causing major demolition, reconstruction works, material loss and waste creation. Three design aspects impacting spatial reversibility were identified in the preliminary design stage: 1) *dimension* of the building block, block floor-to-floor height and façade opening, 2) *position* of the core and load-bearing elements and 3) *core capacity* to carry loads and provide space for services [7].

Technical reversibility is defined as the capacity of systems and elements to be adapted to accommodate change or to be disassembled for reuse by organizing them and defining the relationships between them in a way that will support adaptability, disassembly and reuse [7]. Three design strategies are identified to implement technical reversibility [6]:

- *Functional decomposition* and *functional independence*: definition of functional hierarchy and allocation of functions to separate physical elements.
- *Technical decomposition*: hierarchical arrangement of the physical elements, and hierarchical relations.
- *Physical decomposition*: interface definition between physical elements.

Table 1. Reversible Building Protocol [7].

Design stage	Design objectives	Design strategies
Preliminary design	Spatial reversibility	• Dimension • Position • Core capacity
	Technical reversibility of systems *by functional decomposition*	• Functional independence • Systematization and clustering
Definitive design	Technical reversibility of elements *by technical decomposition*	• Hierarchical relations between elements • Base elements specifications • Life cycle coordination in assembly/disassembly
Technical design	Technical reversibility of elements *by physical decomposition*	• Assembly sequences • Type of connection • Interface geometry

This study compared the Reversible Building Protocol [6] and the Circular Buildings Toolkit [2] to understand how building reversibility is addressed within CBD. The two design frameworks were aligned looking at the design process, design objectives for adaptability, disassembly and reuse, and related design strategies. The design process [5] consists of 5 phases: 1) strategic definition, 2) preparation & briefing, 3) concept design, 4) spatial coordination, and 5) technical design. In terms of strategies, based on the definition of building reversibility [6], design objectives and design strategies related to reuse, design for disassembly and design for adaptability were compared. The comparison is shown in Table 2.

This comparison showed that 1) building reversibility in all its dimensions is not yet fully supported in CBD; 2) building reversibility is not supported at all in the concept design of CBD; 3) spatial reversibility is supported only starting from the spatial coordination stage of the design process; 4) technical reversibility is supported only starting from the technical design stage of the design process; 5) late stages of the building life cycle (manufacturing, construction, use and recovery) are not supported at all in terms of building reversibility; 6) strategies for building reversibility could be embedded in the concept design and spatial coordination stages of the design process to advance CBD in the ability to address spatial and technical reversibility.

Table 2. Reversible Building Protocol vs. Circular Buildings Toolkit.

	Dimensions of reversibility	*Design objectives and strategies*	
		Reversible Building Protocol [6]	*Circular Buildings Toolkit* [4]
1	Building (spatial and technical) reversibility	–	*Refuse new construction* • Reuse, renovate or repurpose an existing asset
2	Spatial reversibility	–	*Increase building utilization* • Increase the multi-use potential of building spaces
	Technical reversibility of systems	–	–
3	Spatial reversibility	• Dimension • Position • Core capacity	–
	Technical reversibility of systems	*Functional decomposition* • Functional independence • Systematization & clustering	–
4	Spatial reversibility	–	*Increase building utilization* • Create the general physical conditions to enable multi-use implementation • Design for increased utilization of regularly "empty" spaces *Design for adaptability* • Choose architectural massing, structural grid and foundation layout compatible with future uses • Allow for changes in building use by designing the building envelope to allow for more than one use or modifications in window size and spacing • Make passive provision accounting for changes to MEP systems and provide a plant replacement strategy

(*continued*)

Table 2. (*continued*)

	Dimensions of reversibility	*Design objectives and strategies*	
		Reversible Building Protocol [6]	*Circular Buildings Toolkit* [4]
	Technical reversibility of elements	*Technical decomposition* • Hierarchical relations between elements • Base elements specifications • Life cycle coordination in assembly/ disassembly	–
5	Spatial reversibility	–	*Increase building utilization* • Design local building performance units for various space configurations and requirements • Make use of versatile/flexible/ movable internal walls for the space layout to support multi-use *Design for adaptability* • Develop and issue an Adaptability Manual document
	Technical reversibility of elements	*Physical decomposition:* • Assembly sequences • Type of connection • Interface geometry	*Design for disassembly* • Develop reversible connections between the structure elements • Allow access to reversible connections between structure and services • Develop and issue a Disassembly Manual Document

2.2 Design Tools

An exploration of existing design tools available to support building reversibility within CBD was performed. It aimed to support an early understanding of current trends and potential gaps. The exploration was limited to insights from existing research and the researcher's experiences. The following set of tools were identified: a) Regenerate [8], b) DGNB Conversion and deconstruction-friendly planning and DGNB Multi-use of areas [9], c) CBC-generator [10, 11], d) Reversible BIM within Digital Deconstruction (DDC) [12], and e) One Click LCA Building Circularity [13]. They were analyzed and compared in terms of building lifecycle and design process stages, design activities and dimensions of building reversibility (Table 3).

Table 3. Design tools comparison.

Tools	*Building life cycle phase*						*Design process phase*					*Design activity*				*Dimensions of reversibility*		
	1	*2*	*3*	*4*	*5*	*6*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*1*	*2*	*3*
a)	●	●								●	●	●			●	●		●
b)		●								●	●	●			●	●		●
c)		●	●		●				●	●	●			●	●		●	●
d)		●		●	●				●	●	●				●		●	●
e)		●								●	●				●			●

Building life cycle phases (adapted from [5]): 1. Strategic Definition & Briefing; 2. Design; 3. Manufacture; 4. Demolition & Construction; 5. Use & Refurbishment; 6. End-of-life.
Design process phases (adapted from [5]): 1. Strategic definition; 2. Briefing; 3. Concept design; 4. Spatial coordination; 5. Technical Design.
Design activities [14]: 1) briefing; 2) analysis; 3) generation; 4) evaluation.
Design dimensions of reversibility: 1. Spatial reversibility; 2. Technical reversibility of systems; 3. Technical reversibility of elements.

The comparison showed that 1) support is mainly focused on the design phase of the building life cycle process. Limited support is provided in the early stage (strategic definition and briefing) and late stages (manufacture; demolition and construction; use and refurbishment; end of life); 2) there are no or limited tools that support the early design phases (strategic definition, briefing, and concept design). Support is mainly provided in the late stages of the design process (spatial coordination and technical design); 3) most of the tools help in evaluation while briefing, analysis and generation are limited supported; 4) designers are mainly supported in the evaluation of solutions in terms of spatial or technical reversibility. Limited support is provided to generate solutions that implement spatial and/or technical reversibility; 5) there are no tools available to support all three dimensions of building reversibility.

3 Matrix-Based Product Modelling Methods

Matrix-based product modelling methods are engineering design methods used to facilitate the modelling of relations in complex systems. They are classified into three types [2]: 1) *Element-level matrixes* represent the relationships between the same types of elements/parts/components of a product or between elements of different types using a matrix; 2) *Product-level matrixes* map the relations between a set of product aspects and product alternatives; 3) *Matrix-based methodologies* use element-level and product-level matrixes to manage complex multidimensional problems systemically and coherently such as the development process or the interactions within products, processes and organizations.

3.1 Axiomatic Design and Design Structure Matrix

AD and DSM are two matrix-based product modelling methods increasingly being used for reversibility in complex systems through modelling relations since the concept design stage.

AD is a matrix-based methodology created by Suh [15, 16]. It provides a design framework with a systematic procedure and general principles to support designers through the design process to model, track decision-making and examine relationships between functional elements and physical components in a structured manner from early design stages. It has been applied to different areas, including non-engineering fields [17] and building design [18], in different stages from synthesis to the evaluation of the synthesized idea, and the selection of the best ideas from alternatives [15, 16]. AD process consists of mapping from problem to solution and from sub-problems to sub-solutions through consecutive design domains (customer, functional, physical, and process domains) and of decomposing hierarchically from general to specific to develop the design in finer levels of detail [15, 16].

DSM is an element-level matrix-based product-modeling method created by Steward [19]. DSM is a representation and analysis tool for system modelling in the design of products, processes, and organizations [20]. In the design of products, it is used for representing relationships and interfaces among components. A DSM process consists of decomposing the system into components, analyzing and quantifying interactions between components in terms of spatial, energy, information, and material, reporting information in a matrix; and grouping highly interactive components in modules [20].

In this study, AD and DSM are proposed to be combined (Fig. 1) to support CBD for building reversibility. AD-DSM can support modelling a building system in terms of functional and technical decomposition and define interactions between its components for physical integration to allow the system to be easily adapted during its lifetime and easily disassembled at the end of its service life for recovery, reuse, refurbishing, remanufacturing or recycling. Specifically, AD can support the implementation of spatial and technical reversibility in CBD. According to [21], this methodology can be applied to building design to implement both spatial and technical reversibility.

AD supports defining functional elements (FRs) and arranging them in physical components (DPs) by mapping FRs and corresponding DPs to implement functional independence. Then, through the zigzagging process, functional decomposition and technical decomposition are performed generating a hierarchy of functional elements, a hierarchy of physical components and hierarchical relations within them. However, through AD, only relations between FRs and DPs are identified for functional and technical decompositions while relations between components for physical integration are not supported.

DSM is proposed to support physical decomposition (and clustering) for building reversibility within CBD. By using a matrix, DSM represents the physical relationship between physical components and groups them into modules by considering the physical connection between components. Although DSM provides a method to model component interactions and group components into modules, it is difficult to generate a design concept by using DSM alone. Also, it assumes that the designer defines functional elements and related functional-uncoupled physical components implicitly.

AD-DSM has been already applied in disciplines such as mechanical engineering [22], product design and manufacturing [23], and construction process management [24] showing complementary benefits while it has not yet been applied to CBD. According to [21], AD can support the design process of analysis, synthesis, generation and evaluation of relationships between functional elements and physical components in a structured manner from early design stages by providing a procedural framework and design principles. DSM can support the modelling of relationships of physical components and group them in modules. So, AD is incapable of analyzing the physical component interactions, which is the great strength of DSM. DSM cannot support the design generation; whilst AD could cover this shortage.

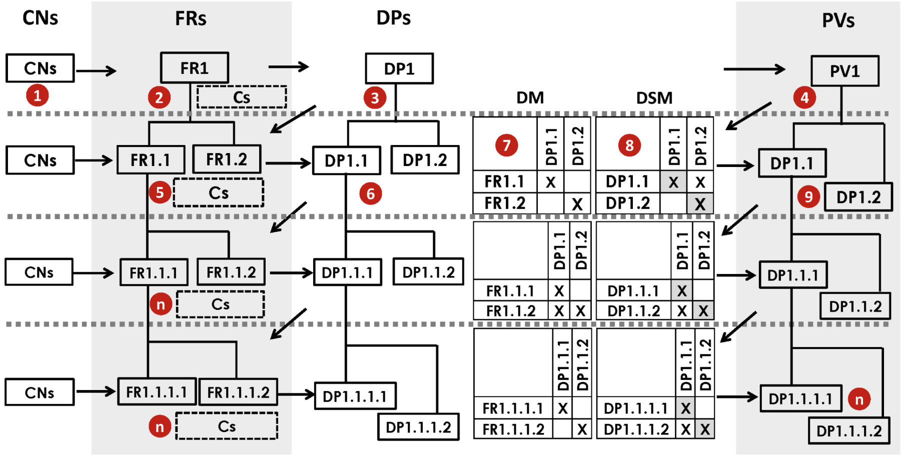

Fig. 1. AD-DSM framework (1. define customer needs (Cns); 2. define the top-level FRs; 3. define the top-level DPs; 4. define the top-level process variables (PVs); 5. decompose the top-level FRs into FRs at the lower levels; 6. define sub-solutions in terms of DPs at the lower levels; 7. check using the design matrix (DM); 8. define relations between DPs using the DSM and cluster DPs; 9. decompose the top-level PVs into PVs at the lower levels)

4 Design Propositions for Circular Building Design

The study defined the following propositions:

1. Within CBD, building reversibility is the ability of a building to be easily adapted during its use to guarantee high transformation potential and then to be easily disassembled at the end of its service life to guarantee high reuse potential of building systems, components and materials. Building reversibility is implemented through three dimensions of reversibility: spatial reversibility, technical reversibility of systems and technical reversibility of elements. However, the design of building reversibility in all its dimensions is not yet fully supported within CBD.

2. The design of building reversibility within CBD is supported by a few tools that mainly support the late design phases (spatial coordination and technical design) while the early phases (strategic definition, briefing, and concept design) are limitedly supported. Most of the tools help in the evaluation of solutions in terms of spatial or technical reversibility while briefing, analysis and generation of solutions to address building reversibility are limited supported. Moreover, no tools are available to support all three dimensions of building reversibility.
3. AD-DSM can support the design of building reversibility in its three dimensions in the early stages of CBD by facilitating functional decomposition, technical decomposition and physical integration. It can support modelling, combining and tracking decisions from the concept design for designing building systems that can be easily adapted during their lifetime and easily disassembled at the end of their service life for recovery. AD guides the designers through the design process to model, track decision-making and examine relationships between functional elements and physical components in a structured manner from early design stages. to implement spatial reversibility and technical reversibility of systems. DSM provides a method for modelling physical relationships among physical components and groups them into modules to implement technical reversibility of elements.

In conclusion, despite the role of building reversibility in CBD, the design of building reversibility is not yet fully supported, especially in the early design stages even if decisions made in the concept design have a strong impact on expected results. The study elaborated the proposition of combining AD and DSM to provide a framework and process in the concept design to model, check and track decision-making for building reversibility within CBD. Current limitations of the study in the literature review, comparative analysis, methodological explanations and lack of applications will be overcome in future research. Literature review, comparative analysis and methodological explanations will be further expanded to consolidate understanding. The theoretical proposition will be tested in the design of circular building components to demonstrate real-world applications while detecting challenges and limitations to assess effectiveness in supporting building reversibility within CBD.

Acknowledgement. This research received support from the COST Action Implementation of Circular Economy in the Built Environment (CircularB) under reference CA21103.

References

1. Abdulaziz A, Martinez-Vazquez P, Baniotopoulos C (2023) Barriers and enablers to the adoption of circular economy concept in the building sector: a systematic literature review. Buildings 13(11):2778
2. Malmqvist J (2002) A classification of matrix-based methods for product modelling. In: International design conference
3. Kubbinga B et al (2018) A Framework for Circular Buildings. https://www.circle-economy.com/resources/a-framework-for-circular-buildings. Accessed 21 Dec 2023

4. Arup & Ellen Macarthur Foundation (2021) Circular Buildings Toolkit. https://ce-toolkit.dhub.arup.com/. Accessed 21 Dec 2023
5. RIBA (2020) Plan of Work 2020 Overview. https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work. Accessed 21 Dec 2023
6. Durmisevic E (2018) Reversible Building Design Guidelines and Protocol. BAMB, report code WP3|10|UT. https://document.environnement.brussels/opac_css/elecfile/06-Reversible-Building-Design-guidelines-and-protocol-note.pdf. Accessed 31 Dec 2023
7. Durmišević E (2018) Reversible building design. Designing for the circular economy, pp 344–359. Routledge
8. Gillott C, Mihkelson W, Lanau M, Cheshire D, Tingley DD (2023) Developing regenerate: a circular economy engagement tool for the assessment of new and existing buildings. J Ind Ecol 27:423–435
9. DGNB (2019) Ckecklists. https://www.dgnb.de/en/sustainable-building/circular-building/toolbox/implementation-checklists-for-your-project. Accessed 31 Dec 2023
10. Van Stijn A, Gruis V (2019) Towards a circular built environment: an integral design tool for circular building components. Smart Sustain Built Environ 9:635–653
11. Wouterszoon JB, Duijghuisen J-A, van Bortel G, Gruis V (2023) Comparing circular kitchens: a study of the Dutch housing sector. Buildings 13(7):1698
12. Durmisevic E, Guerriero A, Boje C, Domange B, Bosch G (2021) Development of a conceptual digital deconstruction platform with integrated Reversible BIM to aid decision-making and facilitate a circular economy. In: Proceedings of the 38th international conference of CIB W78, Luxembourg, pp 902–911
13. One Click LCA, Design more circular buildings. https://www.oneclicklca.com/construction/building-circularity/. Accessed 31 Dec 2023
14. Lawson B (1991) How designers think: the design process demystified, 2nd edn. Cambridge, The University Press
15. Suh NP (1990) The principles of design. Oxford University Press, New York
16. Suh NP (2001) Axiomatic design: advances and applications. Oxford University Press, New York
17. Kulak O, Cebi S, Kahraman C (2010) Applications of axiomatic design principles: a literature review. Expert Syst Appl 37(9):6705–6717
18. Marchesi M, Matt D (2016) Application of axiomatic design to the design of the built environment: a literature review. In: Farid AM, Suh NP (eds) Axiomatic design in large systems: complex products, buildings & manufacturing systems. Springer, Cham
19. Steward D (1981) The design structure system: a method for modelling the design of complex systems. IEEE Trans Eng Manag 3:71–74
20. Browning TR (2001) Applying the design structure matrix to system decomposition and integration problems: a review and new directions. IEEE Trans Eng Manag 48(3):292–306
21. Marchesi M, Matt D (2017) Design for mass customization – rethinking prefabricated housing using axiomatic design. J Architectural Eng 23(3)
22. Tang D, Zhang G, Dai S (2009) Design as integration of axiomatic design and design structure matrix. Robot Comput-Integrated Manuf 25(3):610–619
23. Park S-O, Yoon J, Hochan A, Park J, Park G-J (2021) Integration of axiomatic design and design structure matrix for the modular design of automobile parts. Proc Inst Mech Eng Part B: J Eng Manuf 236(3):296–306
24. Padala SPS (2022) Application of axiomatic design and design structure matrix for early identification of changes in construction projects. J Inst Eng India Ser A 103:647–661