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EMPOWERING CIRCULAR TRANSITIONS: A SERIOUS GAME DESIGNED FOR ENGAGING THE EVOLVING SUPPLY CHAINS AND DIGITAL SOLUTIONS

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Abstract

The transition to a circular economy in the Architecture, Engineering, and Construction (AEC) industry requires coordinated supply chain transitions. Digital tools, such as data-sharing platforms and BIM-based circular design tools, offer potential but remain underutilized, particularly among material suppliers. To bridge this adoption gap, we developed a serious game that connects digital solution developers with AEC professionals, fostering collaboration in circular construction. Tested in a national Growth Fund project, the game simulates real-world challenges, emphasizing needs for data sharing and intermediation. Future integration into lifelong learning programs will equip professionals with the skills to drive circular innovations.

Introduction

The construction and infrastructure sector accounts for 39% of global energy and process-related CO2 emissions, of which 11% originates from the production of materials such as steel, cement, and glass (Global Alliance for Buildings and Construction, International Energy Agency, and the United Nations Environment Programme, 2019). The transition toward a sustainable and circular built environment represents one of the most pressing challenges faced by the AEC sectors. The Dutch construction sector faces the task of building 900,000 additional homes by 2030, a growth of 11%. The required pace for this effort is barely getting off the ground. This is not only because of technical barriers but also because of the complexity of building regulations in this densely populated country. Additionally, there is a replacement and renovation challenge involving approximately 8 million homes and 1 million utility buildings (Circulaire Bouweconomie, 2024). The Netherlands has more than 270.000 companies working in the building sector, mostly micro to small sized companies, which makes the transition not only a technological and design change, but also a behavioral change challenge on a very large scale (CBS, 2024). The transition towards a circular AEC industry is very difficult to impose on people and also requires good collaboration between stakeholders in the chain (Eikelenboom et al, 2021). In the Netherlands, the National Growth Fund (NGF) initiative, "Futureproof Built Environment" (TKI, 2022), seeks to address critical societal issues such as housing shortages, aging infrastructure, and climate change. This initiative emphasizes the need for emission-free, circular, and climate-resilient construction by leveraging industrialization, digital innovation, and cultural shifts.

Digitalization serves as a transformative enabler for the built environment, focusing on open and interoperable platforms to enhance collaboration, streamline processes, and support data-driven operations. The integration of digital platforms into the circular economy value chain—such as lifecycle tracking systems, digital product passports and digital twins—aligns with nation-wide frameworks like the Digitaal Stelsel Gebouwde Omgeving (DSGO, 2025), which proposes standards for secure information exchange and interoperability in the construction sector. However, there is a notable issue with standards in the construction sector. Currently, standardized framework for parametric technologies in construction is lacking, leaving many suppliers, reliant on proprietary solutions and trapped in vendor lock-in. This lack of a unified standard exacerbates the challenges of collaboration and integration across the industry. Studies have shown that digital tools fail to address the nuanced and/ or integrated needs of design, manufacturing and on-site processes facing circular transitions, which call for more advanced functionalities such as lifecycle management and traceability of circular material flows (Yu, et al., 2022). Furthermore, it is stressed that behavior changes are needed to enable the transitions alongside the tooling development (Mies & Gold, 2021).

On the practical side, the NGF's Building Consortium focuses on scaling up sustainable and industrialized construction techniques. Regional living labs serve as experimentation hubs where biobased and circular materials, modular construction, and prefabrication methods are tested in real-world scenarios. One case is the facade supply chain to use biobased materials, such as hemp and wood, for the fabrication of standardized components, fostering resource efficiency and minimizing environmental impacts. Yet, a significant barrier persists: traditional supply chains often lack the

motivation and mechanisms leading to the actual behavior of sharing data critical to enabling digital platforms and facilitating circularity. This disconnection—exacerbated by differing terminologies and digital formats across stakeholders—hinders the seamless integration of circular principles into construction practices. Researchers propose more integrated digital systems to overcome barriers to supply- chain collaboration and data sharing (Munaro, M.R.; Tavares, S.F., 2023). Such initiatives may support operational needs in circular construction, such as circular design, life cycle data management and reverse logistics (Amin et al. 2022; Wu et al. 2022). In this process, more questions are raised not just about the technical aspects, but also how supply chain stakeholders may need to change their ways of working while engaging with the new systems.

To bridge this gap, this paper introduces a serious game designed to address the intersection of these practical challenges. Serious games have been widely recognized as effective tools for engaging stakeholders in complex systems, fostering understanding of trade-offs, and simulating real-world scenarios (Lanezki et al., 2020; Xie et al., 2021). In contrast to existing games that often focus on general concepts rather than operational challenges specific to the circular construction supply chain with emerging digital technologies (Stanitsas et al., 2019), this game equips IT developers and practitioners with insights into the supply chain collaboration processes and information needs for circular construction.

The project background

By focusing on emission-free, circular, and climate-resilient buildings and infrastructure, the National Growth Fund's "Futureproof Built Environment" program (TKI, 2022) seeks to modernize the sector through industrialization, digital innovation, and cultural shifts. Key initiatives include developing biobased and circular material supply chains, and advancing industrialized construction supported by digital platforms. The Futureproof Built Environment initiative integrates a digitalization layer as a critical enabler for transformation within the built environment. This layer focuses on creating an open and interoperable digital platform that enhances value chain collaboration for circularity, streamline processes, and support the shift towards a data-driven sustainable construction market. The digital layer supports circular material flows by linking digital tools to industrial production chains, enabling tracking and integration of biobased and circular materials. Data availability, transparency and ownership are the main challenges.

The Building Consortium, as part of the program, emphasizes industrialized and sustainable construction techniques. It seeks to scale up the use of biobased and circular materials while promoting modular and prefabricated construction methods. The consortium also advances the adoption of standardized building norms and integrates digital solutions that connect stakeholders across the construction value chain. This approach ensures the sector's transformation aligns with broader goals of sustainability, productivity, and climate adaptation.

Together, the digitalization layer and the Building Consortium form the backbone of the initiative, driving efficiency, innovation, and scalability across the Dutch construction and infrastructure sectors which presents a leading European position on circular and sustainable construction. The practical goal is to develop and demonstrate a prototype of a supply chain integration platform (in Dutch: Kringloop Integratie Platform, or KIP), that consist of a number of functionalities. The KIP aims to address the above-mentioned challenges by focusing on parametric technologies, offering a potential bridge to close the gap between these distinct digital ecosystems.

The façade use case

The facade supply chain use case under the "Futureproof Built Environment" program illustrates how biobased and circular materials are integrated into industrialized construction processes. The goal is to transform traditional linear construction models into circular systems that maximize resource efficiency and minimize environmental impact. In this use case, biobased materials like wood, hemp, or straw are used to create standardized, prefabricated facade components. The supply chain is designed to enable scalability and repeatability, leveraging modular construction methods that ensure the facades easy to assemble, disassemble, and recycle.

Digitalization plays a central role in the facade supply chain. In the current practice, few façade supply and building companies have already implemented tools like building information modelling (BIM), manufacturing execution (MES), or enterprise resource planning (ERP). The KIP initiative envisions a federated data sharing platform that links various stages of production, ensuring real-time data exchange between material suppliers, manufacturers, and builders. This platform supports lifecycle tracking of materials, enabling stakeholders to monitor the origin, composition, and environmental footprint of each component. It also connects with broader digital initiatives such as: the Digitaal Stelsel Gebouwde Omgeving (DSGO), which can be seen as a trusted Data Space that complies with the International Data Space principles (iSpace, 2025); the European Digital Product Passport (EU DPP) developed by CEN/CENELEC JTC24 for compliance with the Eco-design for Sustainable Products Regulation (ESPR, 2024); and the United Nations Transparency Protocol (UNTP) for the tracking of authentic supply chain data.

The reality challenge

Even though the transition is needed and mandated (Dutch Government, 2025), and the digital tools are being developed, we see that the traditional supply chain lacks the motives to share necessary data that enables and empowers the digital layer to be functional. The

manufacturers, the constructors and the designers speak different languages. For example, while BIM applications are used by construction companies, the façade systems providers and manufacturers often share information internally and externally in MES systems dedicated to manufacturing. It is therefore difficult to communicate on a supply chain level using standardized formats. Seamless integration of different parties' data in a digital layer to support the circular transitions is challenging. Therefore, there is a strong need to bring the two sides (practice and digitalization) together and let them experience each other's needs, which could facilitate the behavior changes.

Existing games

Transitioning towards sustainable systems often involves addressing complex, interconnected challenges with multiple stakeholders with different interests. Traditional methods of education and engagement may not adequately capture the intricacies of these systems or the competing priorities among stakeholders. On the other hand, serious games offer a dynamic and immersive approach to understanding these challenges. The theoretical underpinnings of serious games emphasize experiential learning as experience plays the central role in the learning process (Hussein et al., 2015). By simulating real-world scenarios, these games could enable participants to explore strategies, understand trade-offs, and build consensus. Several systematic literature reviews have illustrated the different field applications of serious games, such as for sustainability education (Hallinger et al., 2020) and business process management (Machado Leitao et al., 2021). Specifically for built environment transitional challenges, several serious games have been designed to address various transition challenges relevant for the built environment, such as energy systems (Lanezki et al., 2020) and circular economy for urban water (Khoury et al., 2023). Even though they effectively simulate scenarios to engage stakeholders in collaborative decision-making for sustainability and transitions (Dernat et al. 2025), they often focus on general circular or sustainable terms rather than equipping IT developers with deep insights into the nuances of manufacturing processes in the construction sector and facilitate inclusive digital transitions for the industry by involving different perspectives (Speelman et al., 2019). Limited research has given special attention to the interdisciplinary aspects of linking traditional construction industry with the manufacturing industry, which is essential for circular transitions. This results in digital tools that are either too generic or fail to address key operational pain points to link different sectors. On the other hand, these digital tools need to have enough data support to be functional. In order to get those data, users first need to accept and adopt the digital approaches to work before it starts flourishing. Lastly, the experiential cycle of the continuous improvement principle central to both circular economy and the iterative development of serious games should be aligned. In other words, stakeholders should gain valuable insights not only into circular economy strategies but also into ways the serious game itself can evolve, ensuring its ongoing relevance and efficacy in responding to new challenges and technological advancements. For example, digital technologies like XR, AI are emerging quickly and the transitions require constant improvement of the design and learning to be future ready. Therefore, serious games should continuously be improved to reflect the new needs. To be more specific, there are three challenges:

Limited knowledge of manufacturer needs in circular economy

Manufacturing processes in construction involve complex, multi-tiered supply chains with specific information requirements, such as traceability, lifecycle management, and just-in-time inventory. For circular economy, the challenge is currently more pressing on the principles to minimize waste and maximize the use efficiency of resources throughout the whole life cycle of products. Without a structured method for transferring this knowledge to IT developers, digital tools often lack alignment with operational realities from different fields, such as the reverse logistics practice from demolition site to the production of renewed products (Lu, et al. 2023). Therefore, this game aims to familiarize the IT partners with the essential tasks in the manufacturing processes of construction products.

Manufacturers' limited desire for data sharing

Conversely, manufacturers often perceive IT solutions as add-ons rather than integral systems that could transform operations. This perception results in a lack of clear articulation of their informational requirements, such as interoperability, real-time data needs, and user-friendly interfaces. Studies highlight that this disconnection undermines the potential of IT to drive efficiency and innovation, especially while talking about new business models in the circular transitions (Ucar et al. 2020). As observed by a study comparing low-tech and high-tech (digital) serious games for training construction supply chain management practitioners, the cognitive benefits of such games for construction supply chain management are comparable (van den Berg, et al. 2018). Therefore, to enable real-time interaction and discussion, we developed the serious game in a low-tech fashion.

The reflection of multi-stakeholder behaviors and the continuously development

The mutual misunderstanding between IT developers and manufacturers hinders the co-creation of effective tools. While manufacturers may prioritize production schedules and quality metrics, IT companies may focus on scalability and cybersecurity, leading to tools that are technologically robust but practically unfit. The lack of the reflection on the behaviors of multi- stakeholders in the current serious games for generic settings make it difficult to improve the game purpose fully to understand the values behind each behavior during the play and cannot foster further improvement. Therefore, in this game, we have specifically designed reflection sessions to

discuss what has happened during the game from multiple perspectives and use such insights to play other rounds and find improvement potentials.

The designed serious game

This serious game (van Genuchten, 2024) aims to simulate the future scenario and make practitioners (both IT part and the manufacturing part in the circular transitions) understand the practices and the data sharing challenges. The game should ensure that there is an understanding of each other's positions and challenges within the circular value chain, linking AEC and manufacturing of products with digital layers. Players take on various roles representing stakeholders in the construction lifecycle, such as raw material extractors, manufacturers, architects and builders, and waste processors. The game's core objective is to foster understanding and strategic thinking around circular processes, resource efficiency, and sustainable decision-making within construction and the needs for data sharing. Reflection of behavior and choices are essential to foster mutual understanding.

Intended learning outcomes

The serious game is designed to immerse players in the circular construction complexities. By navigating the scenarios, players will be able to:

- Understand material journey from extraction to end-of-life, the reusing or refurbishing potential.
- Understand data sharing needs for transitions.
- Experience circular processes, such as recycling, refurbishing, and sustainable sourcing.
- Recognize the importance of sustainable materials and practices in reducing CO_2.
- Balance economic and environmental factors.

Through this game, players experience circularity and will be equipped with insights relevant to real-world challenges in advancing sustainable and circular construction practices and the information needs in each stage.

Overview of roles and objectives

Each role in the game has specific tasks and goals reflecting real-world activities in the construction lifecycle (Figure 1):

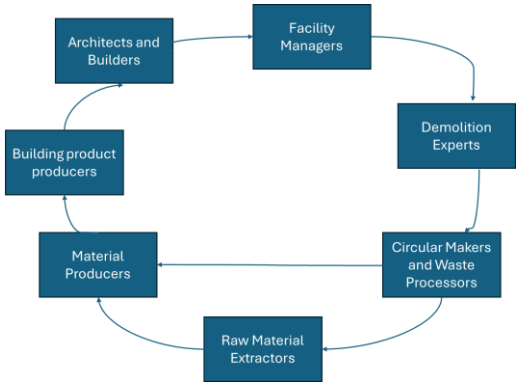

Figure 1: Different practitioner roles in the supply chain

Raw Material Extractors: These roles, like forestry and sand extraction, focus on sourcing raw materials (wood, sand, soda) essential for construction. The objective is to secure revenue by selling these resources while considering environmental impacts.

Material and Building Product Producers: Roles like glass and frame manufacturers involve transforming raw materials into usable construction components/products. They must meet certain production and sales targets, while managing costs and maximizing sustainability impacts.

Architects and Builders: These players are tasked with designing and constructing buildings using the available materials. Architects are encouraged to use parametric design, allowing flexibility in sourcing materials and adjusting designs based on real-time resource availability. Builders, typically contractors, must meet specifications for durability and insulation, simulating the standards in sustainable projects.

Facility Managers and Demolition Experts: They cover building maintenance and end-of-life processes, such as selective demolition, preserving materials for reuse. Players handling demolition manage the financial and logistical aspects of extracting materials with minimal waste.

Circular Makers and Waste Processors: They work on refurbishing and recycling materials. Circular makers refurbish components like window frames, contributing to CO_2 savings and reducing the need for new materials. Waste processors handle collection and transformation, converting items like flat glass into reusable shards.

Game mechanics

The game unfolds in rounds, and players interact based on the materials and skills and the tasks cards assigned (Figure 2). Skills and resources, such as the ability to refurbish wood or produce high-efficiency glass, allow players to perform specific actions aligned with circular economy. The cards also contain hints on how much resource each player possesses at the beginning of each round, such as the amount of cash, raw materials or a set of second- hand products awaiting resale. Each round introduces new rules, challenges and requirements, prompting players to make decisions and make transactions that influence the game's outcome. Such rules are defined to reflect the supply chain dynamics in real practice. They must consider economic, environmental, and social factors while negotiating to achieve their goals. A significant emphasis is placed on collaboration, simulating real-world dependencies.

As mentioned before, it is important to understand the behaviors of players and reflect accordingly. Therefore, players can choose to become an observer to see what happens during the play between the stations and note down what they have seen. In this way, reflection is not only done by the practice role players but also comes from observers, reflecting on the interactions.

Figure 2: Game cards for each practitioner's role, resources/skills and tasks (in Dutch to reflect the reality)

The try out game

To evaluate the game in a real-world setting, we used a consortium meeting as a testbed to observe how the game would function. A simplified version of the game was implemented, consisting of only two rounds. It is important to note that most participants in the consortium meeting were from the IT service sector, contributing to the development of the digital layer of the NGF project. Consequently, the game primarily focused on helping participants understand essential tasks of manufacturers within the supply chain.

How it was played: A circular construction supply chain was designed in which window frames and glass were either recycled, (re)manufactured or reused. Raw materials were also in play, reflecting reality. For different R-ladder strategies, different practitioners were involved in the process for the treatment. For each player, they could choose one role (see different stations for each practitioner role in Figure 1). For each practitioner role in the supply chain, they had specific instructions on their skills/resources and the tasks to perform/objectives to achieve (Figure 2). Players could also choose to become an observer to monitor the process. Once placed at a station, the observer was asked to note who required what information from whom, and whether this transaction was made. For example, the glass maker would ask how much glass was needed and the parametric attributes associated at the station of warehouse and reprocessing of waste.

The rounds: we played two rounds. The first round started with a fixed station and people could only walk one station up or down, as described before, which mimics a more traditional and "linear" supply chain setting. Observers needed to observe what the practitioners discussed and what their tasks and information needs were. It became obvious that these role play professionals needed a lot of time to get into the content to understand their tasks and what information they needed, furthermore they did not know from whom this information could be gathered. The interactions were quite chaotic during this round. In the second round, the practitioners from the supply chain were more familiar with their tasks and needs and therefore knew better whom to ask for extra information. In this round the rule of fixed station was lifted. This round challenged the status quo, and simulated what may happen if more "circular" models like peer-to-peer were introduced. It became more smooth but still chaotic. For example, the same conversations could happen several times and multiple parties would ask one specific party the same information like how much window frames they could deliver, in what condition etc from the client, but the client did not know the exact answer so they needed to consult demolishers. Furthermore, in this second round two extra sustainability requirements were added for two players, stimulating circular choices.

Findings: The game became an eyeopener to see the important roles of the recycle chain. It showed clearly the need to share certain information in the supply and recycle chain to enable circular transitions. It is obvious to see that during the play the need for information gets very obvious if the practitioners want to do their tasks well. However, they have to cross the supply and recycle chain actors to find (if any) information. It is not always successful and the observation from the increased information querying suggests that transaction costs could be higher from an economic perspective when a more circular model is implemented in the supply chain without proper data sharing infrastructure.

Reflections

We can confirm that the game does help actors (IT professionals and supporting professionals in this try out version) familiarize the construction supply and recycle chain tasks and the information needs, evidenced by increased transactions made in the 2nd round. For example, the glass producer knows now the cost of the glass scrips and could make an estimation on how much to produce, making a transaction with the storage and reprocessing facility (circular maker).

On the other hand, it is also observed that during the process, some parts of the supply chain have been cut off due to the fact that information was shared and some facilities already had the capability performing certain tasks that originally should be done by other actors in the supply chain. Therefore, some actors were left out and the transaction was made between actors not directly linked in the traditional supply chain system. We can conclude that data sharing enabled certain facilitators to become more dominant while others might lose their competitive advantage, so it changes the power dynamics in the supply chain. This observation correlates to the theory of "intermediation" in supply chain research and information systems research. The theory perceives the roles of intermediaries as key actors to handle information and disseminate knowledge between stakeholders, and supply chain networks also undergoes the process of "dis-intermediation" as new ties are established throughout a transition process (Cole and Aitken 2020). As highlighted by Ding et. al (2023), the

study of circular supply chains may need to focus more on the in-between roles that create such dynamics. It is also observed that the conflicts between actors are becoming more obvious as some are taking the original tasks of others. During the process (when information is not completely shared) some negotiations are happening among the actors to stay competitive.

The game is designed in a simple form of the supply and recycle chain, however, it can reflect the transitioning process with the information being shared more transparently. During the discussion part after the two rounds, various interpretations were being made, that had not yet happened during other conventional meetings. The practitioners who focus on institutional standards adopted a more holistic view on the circular transaction system and therefore reflect mainly on data sharing with standardized processes. But practitioners who in daily life fulfill a role in the supply chain focus mainly on their daily tasks. We see that there is limited knowledge on the information needs to enable a fully circular value chain as impact evaluation methods are still evolving. Missing roles are also identified like reverse logistics parties.

On the other hand, we found that new processes are emerging with a subset of the whole network and roles may change from traditional tasks towards more holistic operations once the capacity and resources are in place and the risks are managed by measures like data sharing. Industrialization and digitalization could potentially change the whole supply chain into a new paradigm. To enable this, collaboration and resource sharing are rather important to enable resilient project management. We could imagine that in such circular transitions, not all information will be available in the beginning like the needed standards. So it is crucial to follow a resilient "sprint" approach to bridge the top-down institutional guidance and the bottom-up practice oriented initiatives in the future developments.

Conclusions and future developments

The AEC sector faces huge transition challenges globally and NGF program tries to facilitate the transitions with digital layers. However, the digitization levels in the construction and supply chain sectors differ significantly, and this disparity contributes to interoperability issues.

To bring the practice and digital sides closer, a serious game is designed and tried out. This paper contributes to both theory and practice by presenting a low-tech serious game developed for the Futureproof Built Environment program. The game is designed to simulate the circular economy framework within the construction sector, enabling participants to navigate the complexities of supply chain interactions, material lifecycles, and data-sharing requirements. From a theoretical standpoint, it addresses the need for frameworks that enhance cross-disciplinary collaboration and data sharing in circular supply chains and advocates behavior observations and transitions. For the development of serious games, it confirms that continuous reflection based on the experience should be promoted to improve learning experience. From a practical perspective, the game offers a hands-on approach to educating stakeholders, fostering collaboration, and identifying gaps in existing processes. By using the game as a reflective tool, this research provides valuable insights into the evolving dynamics of circular construction supply chains and offers actionable strategies for promoting sustainable practices in the built environment.

The game has shown significant application use in educating actors for specific tasks in the supply chain. It also helps to show how important data sharing is for such transition tasks in the circular supply chain. It also simulates the dynamic and complicated nature of the supply chain and could be used to help actors reflect on the process, designed changes, and potential scenarios. We need to further develop and validate the game in contexts where supply chain parties both from the construction, manufacturing and digital sides are present to understand the business cases.

We aim to use this game further during the project and for educational purposes at the management of the built environment master program to acquaint students with the dynamic and complicated nature of transitions and the importance of information management (starting Nov 2025) and professional learning in summer schools (planned in summer, 2025).

One possibility to further develop and use the game is we use a next version of this game for the design of Digital Product Passports (DPP's), which becomes very prominent (ESPR, 2024). Even though the concepts are well-received, the data content has to be specified. Therefore, a potential use case for the further application of this game is to co-design the DPPs for the façade industry. Furthermore, as this is an European initiative, multiple languages should be also supported with the game.

Another possibility to further develop the game is to incorporate morphological thinking into the game to make it more concrete by creating solid solutions/designs for circular products. Morphological thinking is a structured way used to explore and combine different design parameters and solutions, making them highly effective for circular design. They break down complex challenges—such as material selection, production methods, and end-of-life strategies—into manageable components, allowing designers to systematically generate and evaluate sustainable solutions. By visualizing and combining various options, morphological charts encourage creativity while ensuring alignment with circularity principles like waste reduction, resource efficiency, and regeneration (van Oorschot et al., 2022). Furthermore, based on the business process analysis from the façade industry, it is found that while accounting and resources are very good supported by software (companies want to keep track of their money and their goods); this is not the case for reusing and

remanufacturing purposes (VMRG, 2022). The need for documenting and making available the relevant data for supply chain partners throughout the entire lifecycle should be emphasized and embedded in the game design. We could start with the R-ladders, and we need detailed description of situations. This is to support the situations that when there is a possibility to reduce the use of material with less backward compatibility for components, an assessment needs to be made. To embed this tool and way of thinking in a serious game, the chart could be transformed into an interactive interface where players (e.g., designers, engineers, or students) select and combine different parameters to create circular design solutions not just for new designs but also for existing building stock renovations (backwards thinking with R-ladders as a guidance). The game could include challenges, such as designing a product with minimal environmental impact or optimizing a supply chain for reuse and recycling. Players would earn points for achieving circularity goals, such as reducing carbon footprint or maximizing material recovery. But of course, in such a way, the game is transformed in another format. This gamified approach not only makes learning engaging but also fosters a deeper understanding of circular design principles through hands-on experimentation and problem-solving by linking digital layers and design and manufacturing professionals together in the transitions. Sametime the business case opens for the participants. Last but not least, continuous evaluation of the games based on the user experiences should also be incorporated in the future experiments like quantifiable metrics.

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