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DIGITAL TWIN FRAMEWORK FOR VISUAL EXPLORATION OF MATERIAL FLOWS AND CARBON IMPACTS OF ENGINEERED WOOD SUPPLY CHAINS FROM FOREST TO BUILDINGS

Stephan Ott[1], Andreas Rudena[2], Uwe Kies[3], Anna Wagner[4], Oliver Jancke[5]

ABSTRACT: Engineered wood products (EWP) can achieve a better environmental performance i.e. a lower carbon footprint than most conventional building materials, mostly due to the high carbon storage potential of such products and production processes with lower carbon emissions. Increasing the use of EWP in new built and renovation can thus play a major role for the transformation of the built environment into a large-scale carbon sink. The necessity to make the impact of this use both as a whole and in detail measurable and to directly make the optimization impact visible, the Forest2Building Digital Twin Framework (F2BDF) has been developed. The F2BDF aims at a holistic view of the entire wood construction supply chain and the whole life cycle, including all steps from forest biological production and supply of raw materials, to processing and engineering of products, their installation and use in buildings, and their recovery during deconstruction. The open framework provides a backbone for interconnecting digital twins and harvesting of data across different steps and scales of the supply chain for analytical and predictive purposes. Visual data exploration tools provide insight into material flows, traceability, pinpointing hotspots for optimizing industrial processes, and enable information-based decision making.

KEYWORDS: system, visualization, mapping, supply chain, substitution, environmental impact, resource consumption, circularity, recycling, change management

1 INTRODUCTION

Every consumption has consequences and "[we] are leaving a trail of devastation across the earth with our daily lives, and we don't care […]" [1]. This quote from the German Federal Minister of Economic Affairs and Climate Action was addressed to all consumers in general, but it applies just as much to the economic activities of companies: every action they take has consequences for the environment and especially for the global climate. Unfortunately, many businesses fail to recognize their own trail of devastation by their economic activities. This trail is connected to the entire upstream of resources and generates a significant impact on the global climate, especially in the construction industry. Here the need for lowering emissions through decarbonization actions is very urgent, because resource streams are massive. Due to Greenhouse Gas (GHG) emissions during the use stage and a high share of embodied carbon in products, developing strategies and tools to supervise the way to reach the 1.5 °C climate target is necessary. To meet the climate protection goals of the Paris Climate Agreement, the European Union (EU) has defined targets and measures. Within the scope of the Green Deal, which aims for a climate-neutral Europe by 2050, the EU's Fit for 55 legislative package is now being implemented [2].

Emission reduction or decarbonization as a way towards carbon neutrality in the industry is driven by carbon saving (sufficiency path), carbon reduction through low carbon resources (efficiency), and carbon substitution of fossil-based resources (consistency) by neutral carbon resources, such as bio-based raw materials sequestering CO_2 during growth. Research and development in all three dimensions can enable reduction in real construction projects, new products and innovative and transformative processes on local, regional or even international level. The urgent fields and most powerful levers for the construction industry to implement carbon neutrality are described as follows. Rockström et al. recommend that "[t]he construction industry must either use emissions-free concrete and steel or replace those materials with zero- or negative-emissions substances such as wood, stone, and carbon fibre" [3]. Achieving climate-neutral buildings requires the production of building materials and products that are themselves climate-neutral. This is a significant challenge because resources, transport, and processing require auxiliary substances and energy,

[1] Stephan Ott, Technical University Munich, Germany, ott@tum.de
[2] Andreas Rudenå, Paramountric, Sweden, andreas@paramountric.com
[3] Dr. Uwe Kies, InnovaWood, Belgium, uwe.kies@innovawood.eu
[4] Anna Wagner, Technical University Munich, Germany, anna.wagner@tum.de
[5] Dr. Oliver Jancke, InnovaWood, Belgium, oliver.jancke@innovawood.eu

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resulting in environmental impacts from emissions to air, water and soil, which must be avoided [4].

There are several ways to reduce emissions, including avoidance strategies such as using alternative materials and technologies that produce little to no emissions or compensating for excess emissions through appropriate carbon neutral technologies or raw materials themselves. Additionally, building components and materials must be processed after dismantling, then be reused or recycled for secondary use, which again requires energy, technologies and auxiliary substances. Therefore, achieving a climate-neutral building in its entire life cycle requires two main tasks: i) optimizing the building to zero-emission operation itself over its useful life and ii) producing and dismantling the building and its materials in a way that generates no emissions or even sequesters CO_2 [6]. Making the supply chain more sustainable has very positive implications: companies and other actors will begin toavoid the path of destruction and take effective action towards protecting the climate through decarbonization and emissions reduction [7].

This exploratory essay studies how a digital framework can be created which can address and reduce environmental impacts and help to implement these strategies in the scope of the *BASAJAUN* project. We focus on decarbonized raw material transformation and logistics of EWP and bio-based materials in modular and hybrid building solutions, sequestration and long-time storage of biogenic carbon in bio-based construction products, and substitution of fossil carbon use, and innovative circular concepts, such as side streams, reuse, and recycling. *BASAJAUN* is a major European innovation action about sustainable building with wood. The main objective is to demonstrate with wooden demo buildings, how wood construction chains can be optimized to foster both rural development and urban transformation whilst being connected with sustainable forest management in Europe.

Our goal is to better understand the mechanisms behind the trail of devastation caused by economic activities and gain deeper insights into the eco-industrial system which at its core consists of supply chain networks. Through better information of connections and data from places of transformation in all networks, and by tracing end products back to their origins and examining raw material extraction, resource flows and processing, we can better understand the impact of supply chains on GHG emissions and value creation.

2 BACKGROUND

2.1 Product integration in sustainable construction

Integrators, such as timber construction companies, face multiple challenges, such as incorporating various eco-friendly precursors into their integrated end products. To manage the supply chain according to sustainability goals, data on technical product specifications, resource consumption, environmental impact, health, origin, manufacturing, and corporate governance must be collected and analyzed from the entire supply chain.

To achieve optimal product performance, integrators require an overview of a complex and multi-layered supply chain, along with the ability to collaborate with suppliers throughout the development process. The overall supply chain system is the bioeconomy, and its sub-systems addressed are originating from renewable resources cultivated in agriculture and forestry. The supply chain comprises various transformation stages of the raw material from first to second and following Transformation Production Systems (TPS), comprising their main product streams but also side streams. Tier Suppliers (TIER) is a method of organizing different suppliers into categories in order to delineate which materials are most important in your supply chain. Organizing suppliers into TIERS can stimulate better, necessary communication between a company and its suppliers. Understanding the system and its sub-systems with their interwoven production and supply chain hierarchy helps to trigger necessary transformation processes of the entire TPS to manage it more sustainably. *Industry 4.0* with its connected production systems that are designed to monitor, predict, and interact with the physical world, to enable decisions that support production in real- or right time, offers a technology approach to map the (micro) sub-systems of the wood supply chain as a macro eco-industrial system, visualize their interrelationships, and extract specific, characteristic data from almost all points in the system. With this characteristic data, the state and behavior of the system can be identified in the event of changes and managed in a targeted manner. However, keeping the data simultaneously up-to-date, consistent with the final product and adaptive to changes during the design, tendering, order, delivery, and construction process of each project is a significant challenge for the digital system design.

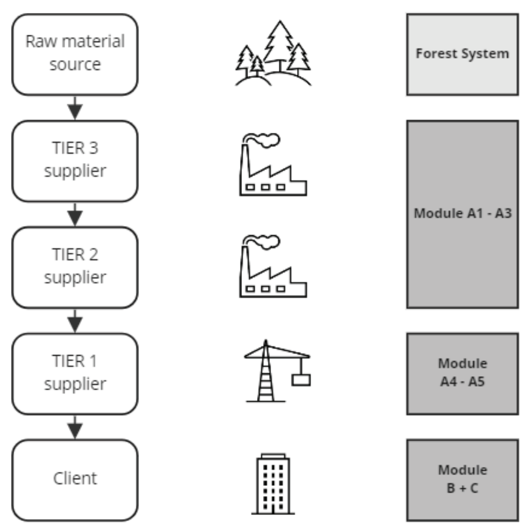

Figure 1: *Integrators deliver complex products or components by integrating lower-level suppliers' products*

The primary goals are to reduce GHG emissions and to close resource loops in supply chains. It is essential to

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reduce primary resources, increase the use of secondary raw materials, increase durability, use renewable raw materials, and expand the CO_2 storage potential, which is especially high for renewable resources. However, the comprehensive knowledge needed to make informed decisions is often not available and sufficiently transparent, which makes it difficult to change established patterns of action and select products that are suited to build in a climate-, resource-, and recycling-friendly way. The main points of interest are the system build-up by means of the digital backbone F2BDF, which offers capabilities for mapping and visualization of resource flows within the chain, trace back raw materials to their upstream origin, follow their split into diverse products downstream, and target the resources and emissions along all processing steps.

2.2 SCM challenges in construction industry

In the construction industry, the supply chain faces several challenges, including complex and changing requirements of building projects, limited visibility and poor communication, limited supplier options and long lead times, and a lack of standardization on many levels. Effective supply chain management can improve efficiency, reduce costs, and increase customer satisfaction. Key strategies include efficient inventory management, transportation optimization, and effective communication and collaboration among supply chain partners.

Supply chain management (SCM) is a critical aspect of any industry. In the construction industry, managing the supply chain is especially challenging due to several unique factors. In this section, we will examine the challenges that SCM faces in the construction industry.

The construction supply chain involves a network of organizations and individuals that work together to design, produce, and deliver products and services to customers. This process includes sourcing raw materials, manufacturing, transportation, and distribution of products. Effective SCM can improve any businesses performance. To achieve these benefits, key strategies must follow each step and decisions along the supply chain and check and verify its compatibility with lowered impact on resource consumption combined with environmental impact as well as social and governance objectives.

Despite these benefits, the construction industry's supply chain faces several challenges. One of the most significant issues is the complex and changing project requirements. Construction projects are often large and complex, with changing requirements and tight deadlines. This can make it difficult for supply chain partners to plan and coordinate effectively, leading to delays, increased costs, and potential quality issues.

Another challenge is limited visibility and poor communication. Construction supply chains often involve multiple parties, such as architects, engineers, contractors, and subcontractors. Poor communication and a lack of visibility into the actions and decisions of other supply chain partners can lead to delays, errors, and increased costs.

Furthermore, some materials and equipment used in construction, such as steel and concrete, have long lead times and limited supplier options. This can make it difficult for supply chain managers to ensure that materials are available when they are needed, leading to delays and increased costs.

The lack of standardization is also a challenge in the construction industry's supply chain. This sector often involves a wide range of materials, equipment, and systems, with limited standardization. This can make it difficult for supply chain managers to ensure that materials and equipment are compatible and that quality standards are met.

Site-specific logistics is another issue that supply chain management must consider in construction. The construction site can be remote and difficult to access, requiring specialized logistics and transportation. This can include using heavy equipment and cranes to transport materials, as well as managing the logistics of waste disposal and recycling.

Safety and quality control are also critical considerations in construction supply chain management. Construction projects have a lot of risks, such as accidents and quality control issues. SCM must ensure that all materials and equipment meet safety and quality standards, and that adequate safety measures are in place to protect workers.

Finally, construction industry supply chain management must ensure compliance with regulations and standards on environmental protection, waste management, and recycling. This involves ensuring that all materials and equipment are environmentally friendly, and that adequate measures are in place to protect the environment.

2.3 Sustainable transformation of supply chains

Supply chains play a significant role in sustainable development. Sustainable transformation of construction supply chains is a complex and challenging process that requires the creation of new supply chains and their integration into existing business processes. In the bioeconomy, sustainable supply chain transformation is necessary to produce environmentally friendly products. The timber construction industry, as integrators, faces multiple challenges, including the incorporation of improved and eco-friendly precursors into integrated end products. Collaborating with suppliers throughout the development process can achieve optimal product performance. Data on various technical specifications, resource consumption, environmental impact, health, origin, manufacturing, and corporate governance must be collected from the supply chain to trigger necessary transformation processes of the system to manage it more sustainably.

The overall goal is to reduce greenhouse gas emissions and close resource loops in supply chains. The challenge is how to make informed decisions and select products that are climate-, resource-, and recycling-friendly.

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2.4 Environmental challenges in construction SCM

The construction industry faces various environmental challenges that impact SCM. These challenges arise from environmental regulations and standards that demand strict compliance, sustainability considerations, carbon footprint reduction, and penalties for non-compliance. Additionally, the industry's reputation can suffer when it fails to meet environmental standards, leading to lost business opportunities.

Compliance with environmental regulations is vital in the construction industry, given its potential for negative impacts on the environment. These regulations may cover air and water pollution, hazardous waste disposal, and the use of certain materials and chemicals. To meet these regulations, supply chain managers must ensure that all materials and equipment used in construction comply with the required standards. Moreover, they must implement measures to protect the environment adequately.

Sustainability considerations are crucial in construction projects, which can have significant impacts on the environment. Supply chain managers must take steps to ensure that materials and equipment used are environmentally friendly. This includes sourcing from suppliers with sustainable certifications and promoting sustainable practices such as recycling, reducing energy consumption, and water usage.

Reducing the carbon footprint is another critical aspect of environmental SCM in construction. Supply chain managers must evaluate GHG emissions produced throughout the product life cycle and develop strategies to reduce them. This evaluation ranges from sourcing raw materials to final product disposal.

Non-compliance with environmental regulations can lead to significant penalties and fines, impacting companies' finances and reputations. In some cases, non-compliance can lead to legal action and suspension of construction projects. Additionally, companies that fail to meet environmental regulations and standards may struggle to win new business opportunities, impacting their reputations.

In conclusion, environmental challenges are significant for the construction industry and require a proactive approach in SCM. Effective strategies include compliance with regulations, sustainability considerations, carbon footprint reduction, and avoiding penalties and reputational damage. By addressing these challenges proactively, companies in the construction industry can gain a competitive edge while contributing positively to the environment.

2.5 Problem of GHG emissions reduction and closed resource loops in supply chains

As companies strive to reduce their environmental impact, they must consider how they can make decisions both as individuals and as representatives of the industry to reduce their use of primary, fresh resources and increase the use of secondary raw materials. This includes increasing product durability, using renewable raw materials, and expanding the potential for CO_2 storage, which is high for renewable resources. However, it often lacks comprehensive knowledge and transparency about the resources they use and the impact they have, making it challenging to make informed decisions and change established patterns of action.

To address this issue, companies need to narrow down the objects and subjects of knowledge and decision-making problems, focusing on the origin and production of materials and their effects in the industrial context. By doing so, they can formulate ways to build in a climate-, resource-, and recycling-friendly way.

To achieve this goal, we propose a digital backbone called the Forest-to-Building Digital Twin Framework (F2BDF) to companies, which uses mapping and visualization to analyze resource flows within the system. With F2BDF, they can trace the origin of raw materials upstream and their transformation into various downstream products. This allows them to target resources and emissions along processing steps and identify areas for improvement.

By implementing this framework, businesses can build a more sustainable and environmentally friendly industrial system by reducing GHG emissions and creating closed resource loops in supply chains.

2.6 Disrupting the supply chain

The wood construction industry is undergoing a digital transformation, with a clear vision presented by thinkers, innovators, and makers on the frontline. One aspect of disruption is the rising effort in integration of preliminary products into a prefabricated and integrated end-product. This integration is increasingly important for both large and small projects, as clients expect the end-product to fulfill superior properties, such as load-bearing, fire resistance, and other functions related to weather protection and resource-saving. The integration is expected to result in higher quality, improved manufacturing quality, on-time delivery, waste reduction, and faster construction activities.

However, to achieve this level of integration and quality, a detailed understanding of the supply chain is key. This includes the flows, stocks, processes, and upstream data that are characteristic for each product. This data is critical to enable sustainable, integrated, prefabricated, quality-controlled, durable, and on-time building projects. The concept of *Industry 4.0* and the *Internet of Things* (IoT) can help us see the big picture and system connections of Sustainability Supply Chain Management (SSCM) [8].

To achieve this goal, we propose a Digital Twin Framework for visual exploration of material flows and carbon impacts of engineered wood supply chains from Forest to Buildings. Digital twins can provide a virtual representation of a product or system, which can be used to optimize its performance and sustainability. In addition, the use of sensor data, real-time data, big data, machine learning, data mining, data analytics, simulation, and optimization can help to leverage the supply chain into a more sustainable direction.

The F2BDF will allow to analyze the entire supply chain from forest to buildings and identify areas where

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improvements can be made. The framework will incorporate all data related to the supply chains of products and building materials, their origins, transparency, and impact on GHG emissions and value creation, allowing for a more sustainable and environmentally friendly system.
By using these concepts and technologies, the wood construction industry can transform its supply chain and create more sustainable and efficient projects. It can help to reduce waste, improve quality, and create more sustainable products that meet the needs of clients and consumers. With a focus on advanced SSCM and digital transformation, the wood construction industry can lead the way in creating a more sustainable economy.

3 METHODS AND DATA

3.1 Generic system representation and visualization

Development of the description of a generic system representation and the need of F2BDF backbone and other digital tools in combination with visualization tools, material flow tools as Sankey, LCA tools. Plus, the "resource" data from the digital twins, i.e. glulam factory, building design, and others.
The overall system of supply chain is the bio-economy and its sub-systems addressed are based on nature and renewable resources cultivated in agriculture and forestry and harvested from nature. The focus is dedicated to the timber supply chain from the forest over sawmills and downstream until urban timber buildings. The supply chain comprises various transformation stages of the raw material from first to second and following TPS with their main product streams but also side streams (logs, beams, wood cut-offs or particles, timber construction products, timber buildings).
We need this understanding of the system and sub-systems with their interwoven production and supply chain hierarchy to recognize single entities, dependencies, and routes between each of them. In an advancing digitalization through *Industry 4.0* concept, it is possible to map the (micro) sub-systems of the wood supply chain itself as macro eco-industrial system, visualize them in their interrelationships, and more importantly, extract specific, characteristic data from almost all points of the system. With this characteristic data, the behavior of the system can be read off in the event of changes and managed in a targeted manner.
We started to give a first overview on the necessary data pertaining to technical product specifications, resource consumption (including material, energy, and water usage), environmental data (including emissions), health data, origin data, manufacturing data (including social aspects), and corporate data (including governance). All this data changes continuously updated, and needs to be kept up-to-date, consistent with the final product and with changes during the design, tendering, order, delivery and construction process of each project.

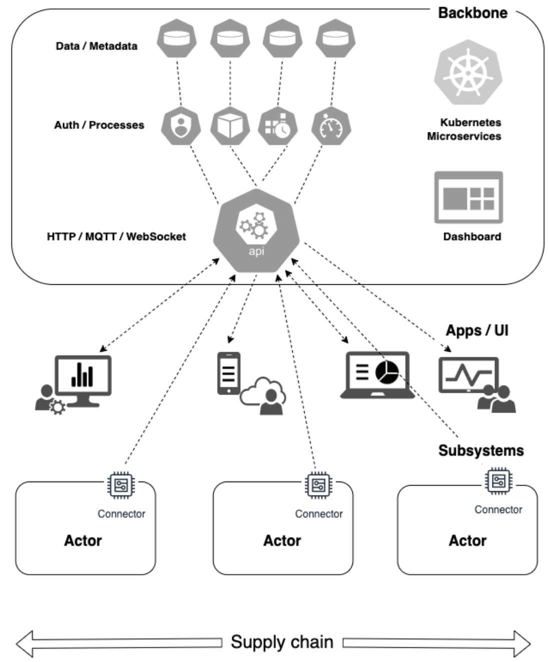

Figure 2: *System architecture of F2BDF*

3.2 Description of the F2BDF and Backbone

In the light of the *Industry 4.0* digitalization and automation transition a lot of work has been done in the area of systems interoperability. The F2BDF is specifically inspired by the *OPC UA* standard where information models can be used to define this interoperability layer with schema representation.
One challenge with the timber construction wood value supply chain is that it spans several industries and data domains making it difficult to rely on existing information models and schemas for data interoperability. A common and complete information model for the forest-to-building supply chain across Europe does not exist. Work could potentially be spent trying to define such data format for the full supply chain. However, taking into account the diversity of actors and traditions between countries this would not be feasible in relation to time and resources available in the *BASAJAUN* project. This work would also likely need to be connected to work in standardization and alignment in and between many domains that composes the wood material to building construction and life cycle supply chains. Instead, a more dynamic "data first" approach is proposed here based on bottom-up principles, where company data is collected and analyzed using flow visualization, and then mapped to indicators built through common understanding.
The studied approach for flexible data collection looks into work with digital twin city implementations where interoperability between actors and their data, products and artefacts, a similar major challenge can be identified as the diverse interconnections are quickly expanding. The change management in such a system with hundreds or thousands of actors is a challenge, and full

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interoperability is still only theoretically imaginable. This is also connected to a wish to get started with sustainability work immediately and not wait for an industrial agreement or standard committees to finalize their work potentially still not reaching industrial consensus due to systemic boundaries and abstractions that in the end still does not fit some of the actors.

3.3 Mapping and Visualization of the Supply Chain

First, the F2BDF backbone is the representation of the entities; in the next step, the entities are connected, and their interrelationships and interaction options are represented. Here, the data can already be entered into the entities or transferred from sensors into the backbone. Through the representation as Sankey chart, it is possible to visualize the material flows between the entities and the size of the flows is represented proportionally. Main flows and gaps in the flow become visible. Side streams can leave the flow for other manufacturing processes and new side streams can be added, for example from secondary sources, if linearly thought in up- and downstream. The representation clarifies which quantities are on the way where in the system at point in time *x*.

4 RESULTS AND DISCUSSION

4.1 Analytics of the Supply Chain

The analytics of supply chains are an essential aspect of managing and optimizing the flow of goods and services from raw materials to finished products. One methodological approach to analyzing the supply chain involves the use of the forest-to-building digital framework introduced above. This framework collects data on raw materials, intermediary products, and end products as they move through various production systems, allowing for a comprehensive view of the entire supply chain.

Scientific and operational analysis of structured data from a production network involves various techniques such as network analysis, flow analysis, machine learning, prediction, scenario building, and concept verification.

Machine learning techniques can be used to analyze structured data from a production network to identify patterns and predict future trends. For example, machine learning algorithms can be used to predict demand for specific products, identify maintenance needs for machinery, or optimize production schedules. Scenario building involves using data from the production network to simulate different scenarios and identify potential outcomes. This can be used to evaluate the impact of different decisions or changes to the production network. Concept verification involves using data analytics to verify the effectiveness of new concepts or ideas in the production network. For example, a new production process can be simulated using data analytics to evaluate its feasibility and potential impact on the network. Other examples of data analytics for structured data from a supply chain and production network include:

- Quality control analysis to identify patterns of defects and improve product quality,
- Inventory management analysis to optimize inventory levels and reduce waste,
- Sustainability analysis to evaluate the environmental impact, circularity of the production network and identify areas for improvement,
- Risk analysis to identify potential risks and develop mitigation strategies.

4.2 Supply chain management and LCA

Digitalization has the potential to greatly enhance the integration of SCM and Life Cycle Assessment (LCA) [7]. Digital technologies can support the collection, analysis, and communication of data throughout the entire life cycle of a product, from the sourcing of raw materials to the disposal of the final product. Data collection and analysis: Digital technologies such as sensors, Internet of Things (IoT) devices, and cloud-based platforms can be used to collect data on the environmental impact of products and materials throughout their entire life cycle. This data can then be analyzed to identify areas of improvement and support decision making [7].

Collaboration and communication: Digital technologies such as Electronic Data Interchange (EDI) and Enterprise Resource Planning (ERP) systems can be used to improve collaboration and communication among supply chain partners [10]. This can include sharing information and tracking orders in real-time, improving coordination and reducing errors and delays [11]. In addition, applications such as social-LCA can be carried out with transparent supply chain documentation [13].

4.3 Data collection possibilities and needs

4.3.1 Tracking data and network analysis

Tracking data is an essential tool for identifying the origin of the materials used in construction, particularly the glulam used in the demo structure. By tracing the journey of wood through all the different locations and means of transportation, it is possible to pinpoint the forest stand from which the raw material originated. This process involves a location-based scenario that helps track the origin of wood backward from its source. Network analysis is a crucial aspect of this process, as it allows for optimization of the production network by identifying key nodes, bottlenecks, and dependencies, which can lead to improved efficiency and resilience.

Furthermore, linking the backtracked data to external certification label databases, such as the FSC/PEFC label database, can provide clients with additional information about the origin of the wood, such as logging type used in the forest and the sustainability and environmental friendliness of the materials used. This additional information can enhance transparency and improve client understanding of the materials used in the construction process. Apart from the logistics chain application, the backtracked data also help in quality control by detecting and querying wrong or damaged supplies in the chain, leading to better-quality products. The process of backtracking data and analyzing the production network

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topology, together with linking to external certification label databases, can provide useful data for clients, including machine learning, prediction, scenario building, and concept verification.

__Figure 3:__ Tracking locations of production from raw materials extraction to construction sites of Northern (Finland) and Southern (France) demos

In summary, backtracking data are a valuable tool for tracing the origin of materials used in construction, and network analysis can optimize the production network and improve efficiency and resilience. Linking to external certification label databases can provide clients with more detailed information about the sustainability and environmental impact of the materials used, while other forest-related information, such as logging type, can improve transparency and client understanding. Overall, the use of backtracking data and network analysis provides critical insights for the quality control and optimization of production networks in construction.

4.3.2 Environmental and sustainability data

The responsible use of resources and minimization of the impact of industrial processes on the environment are critical aspects of sustainable development. This can be achieved through collection and analysis of environmental and sustainability data. One important aspect is tracking the quantity of raw material flow and assessing the loss of wooden raw material throughout the supply chain. To accomplish this, producer- and quantity-based scenarios can be implemented. By tracking the flow of raw materials from the forest to the final product, it is possible to measure the net mass and volume at each stage of transformation and determine the amount of timber lost during processing.

At the sawmill, the gross volume of wood can be measured along with the output of the cut boards and their net volume, weight, and moisture content. Side streams, such as bark, sawdust, and low-quality wood, sorted during processing should also be documented. Intermediate wholesalers or refiners can also be included in the tracking process to measure the gross in and net out of wooden material, as well as any side-streams produced. At the glulam factory, the gross in of the boards can be measured along with the net out of the glulam beams and their volume. Side streams, such as quality sorting waste, cut-offs from finger jointing, and wood shavings from planing should also be documented. Finally, at the

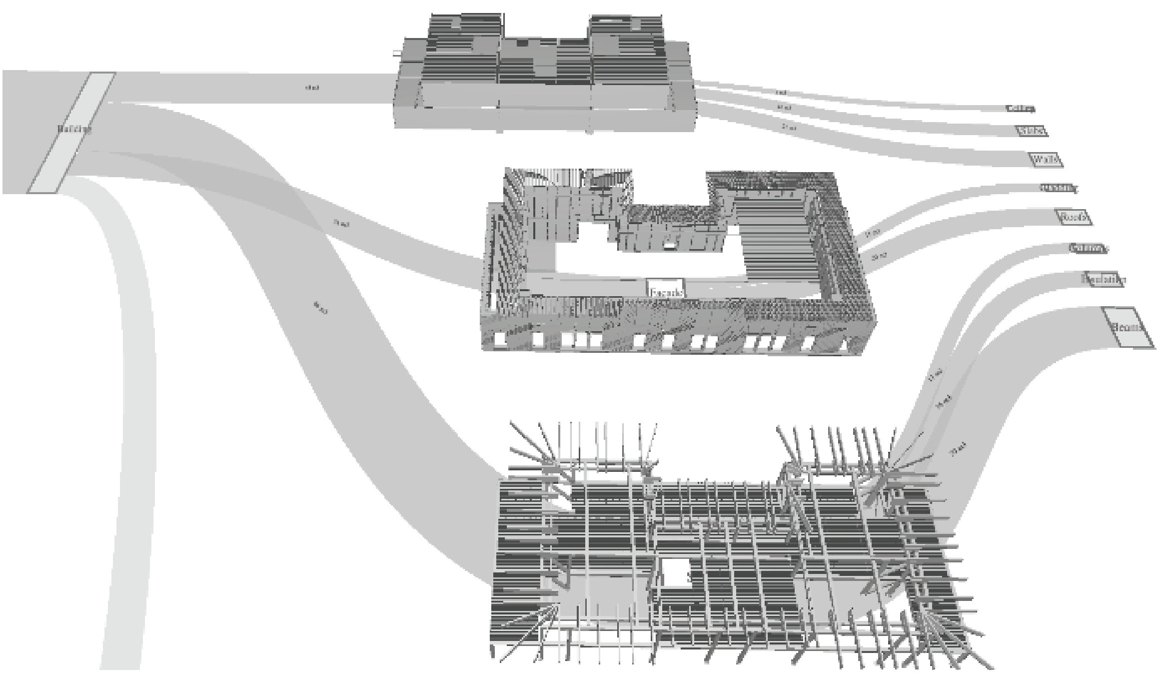

__Figure 4:__ IFC model of demonstrator connected to glulam Sankey chart of F2BDF backbone

construction site, the gross in of the wooden material can be measured along with the net amount used in the structure.

By tracking all stages of production and linking with environmental impact data, it is possible to obtain a comprehensive picture of the supply chain's environmental impact. This information can be used to identify areas where improvements can be made, such as reducing the loss of raw materials or finding more sustainable methods of production. Additionally, BIM (Building Information Modelling) can be used in construction projects to ensure that materials and equipment are compatible with BIM systems and that BIM data are shared and integrated with all stakeholders, see [12]. The data collected can be linked to the BIM model, enabling stakeholders to visualize the environmental impact of the construction process and identify opportunities for optimization. Environmental performance tracking with digital tools such as digital dashboards, data visualization, and analytics can be used to track and monitor the environmental performance of products and materials throughout their life cycle. This can help supply chain managers to identify areas for improvement and to make data-driven decisions.

In summary, the collection and analysis of environmental and sustainability data are crucial for responsible resource use and minimizing the impact of industrial processes on the environment. Tracking the quantity of raw material flow and assessing the loss of raw wooden material throughout the supply chain can be achieved by measuring the net mass and volume of each stage of transformation. This information can be used to identify areas where improvements can be made, and BIM can be used to integrate the data and optimize the construction process.

4.3.3 Auxiliary streams and co-products

Flow analysis focuses on the movement of materials and products through the production network. By analyzing

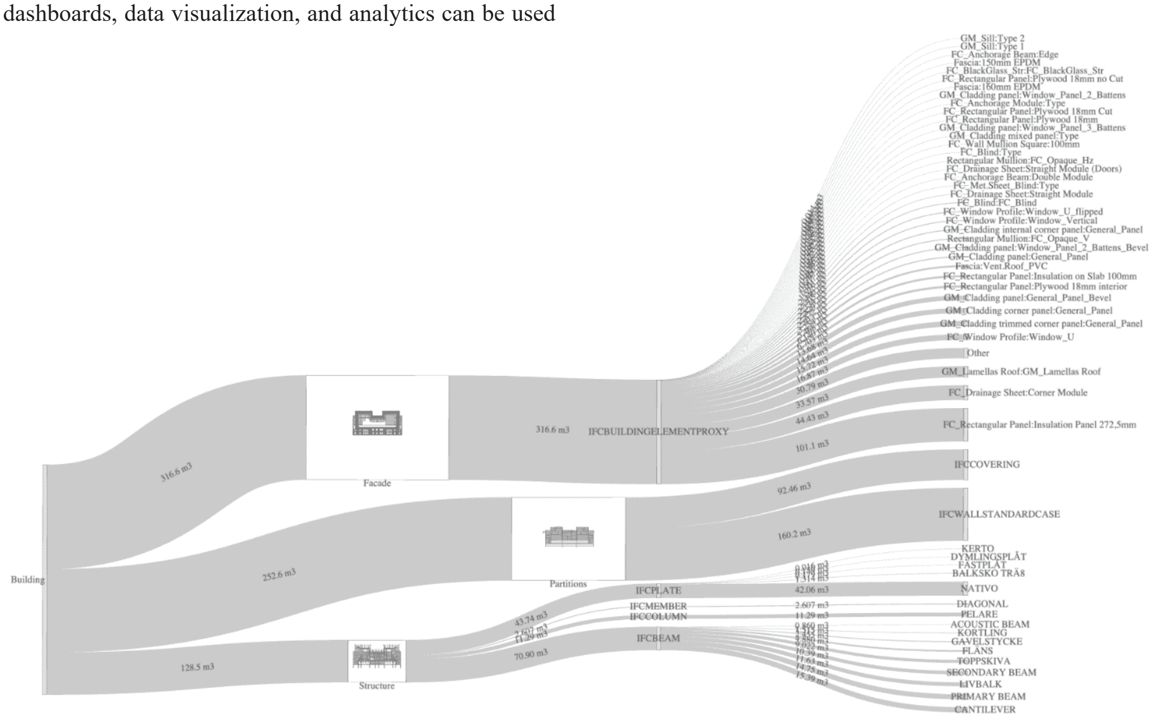

Figure 5: *Full Sankey chart of material flow from forest to building visualized from F2BDF backbone*

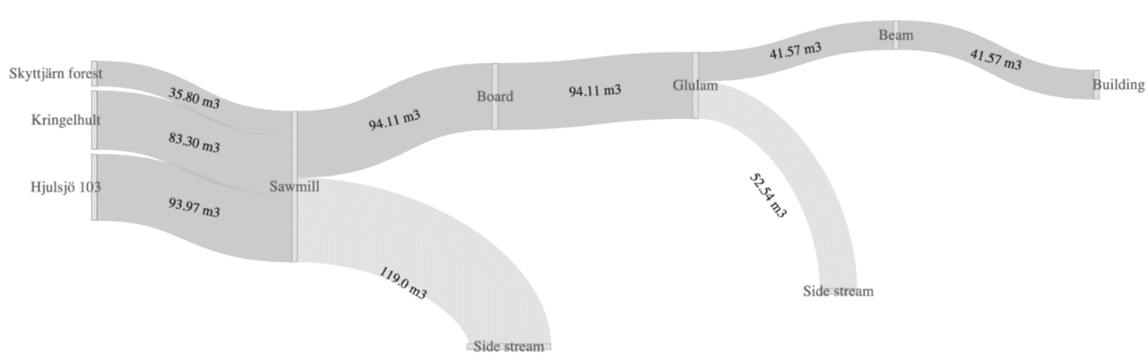

Figure 6: *Exemplary auxiliary streams of co-products taking place during the production of glulam from forest raw materials*

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the flow of materials and products, bottlenecks and inefficiencies can be identified and addressed.

To better understand the flows in production of glulam, it's important to look not only at the main raw materials used but also at the auxiliary flows that are needed in the production process. This includes energy, glue, and other supplies. It's important to track these flows in each main production stage/phase and determine the quantity, supplier, and location of these supplies.

A flows-based scenario would be useful in analyzing other interesting flows in each main production stage/phase. For example, tracking energy flows for harvesting, sawmill operations, and drying of the wood would provide insight into the energy usage of the production process. Additionally, tracking the energy and emissions generated during transport would provide valuable data. Side streams, such as glue and packaging materials, should also be considered. It's important to track these materials at each step of the transformation process and determine their origin, quantity, and disposal method. Understanding the auxiliary flows and side streams of glulam production is crucial for identifying areas where sustainability and efficiency improvements can be made.

5 CONCLUSIONS

In conclusion, achieving climate-neutral buildings is an urgent goal that requires significant changes in the way we produce, use, and dispose of building materials and products. By applying the principles of efficient raw material transformation, long-time storage of biogenic carbon, innovative circular concepts, and using a Digital Twin Framework for Visual Exploration of Material Flows and Carbon Impacts of Engineered Wood Supply Chains from Forest to Buildings, we can make a difference and support the urgent goals of exceptional amounts of carbon reduction, up to carbon neutrality and positivity. We want to make the resource consumption that takes place in complex, interwoven systems visible and comprehensible, so that we are not overwhelmed by the complexity and confusion. We will need digital tools and *Industry 4.0* technology that helps to extract siloed data to allow us to map the current systems, especially the raw material and energy flows within them, to identify their quality, quantity and potential problems. From this, the next step is to think about change and to anticipate and understand the effects of change to be able to take corrective action if necessary or to control the change process.

As shown in the *BASAJAUN* project digital tools can be used to collect data about sustainable sourcing, identifying and tracking the environmental impact of products and materials throughout their life cycle. This can include using F2BDF digital tools to track the environmental impact of suppliers, identify sustainable materials and products, and monitor the environmental performance of logistics providers. Once these data are collected, there are various possibilities for their analysis which have to be done in follow up studies.

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REFERENCES

[1] R. Habeck: In *Talk Show Lanz*, ZDF, 31.03.2022.

[2] European Commission: 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality, 2021.

[3] J. Rockström, et al.: A roadmap for rapid decarbonization. *Science*, 355(6331), 1269-1271, 2017.

[4] M. Kuittinen, A. Organschi, A. Ruff.: Carbon: A Field Manual for Building Designers. Wiley, 2022.

[5] European Parliament: What is carbon neutrality and how can it be achieved by 2050. Online https://www.europarl.europa.eu/news/en/headlines/society/20190926STO62270/what-is-carbon-neutrality-and-how-can-it-be-achieved-by-2050, 2020.

[6] G. Churkina, et al.: Buildings as a global carbon sink. Nat Sustain 3: 269–276, 2020.

[7] Dadhich, P., Genovese, A., Kumar, N., Acquaye, A.: Developing sustainable supply chains in the UK construction industry: A case study. In *International Journal of Production Economics* 164, 271–284, 2015. DOI: 10.1016/j.ijpe.2014.12.012.

[8] T. Saurabh: Supply chain integration and Industry 4.0: a systematic literature review. In *Benchmarking: An International Journal* 28 (3), 990–1030.,2021.

[9] OPC FOUNDATION: OPC UA online reference: https://reference.opcfoundation.org/, 2023.

[10] Seuring, S., Müller, M.: From a literature review to a conceptual framework for sustainable supply chain management. In *Journal of Cleaner Production* 16 (15), 1699–1710. 2008. DOI: 10.1016/j.jclepro.2008.04.020.

[11] Tuni, A., Rentizelas, A., Chinese, D.: An integrative approach to assess environmental and economic sustainability in multi-tier supply chains. In *Production Planning & Control* 31 (11-12), p. 861–882. 2020. DOI: 10.1080/09537287.2019.1695922.

[12] Xue, K.; Hossain, M. U.; Liu, M.; et al.: BIM integrated LCA for promoting circular economy towards sustainable construction: an analytical review. In *Sustainability* 13 (3), 1310-1331. 2021. DOI: 10.3390/su13031310.

[13] Benoit-Norris, C.; Cavan, D. A.; Norris, G.: Identifying social impacts in product supply chains: overview and application of the social hotspot database. In *Sustainability* 4 (9), S. 1946–1965, 2012. DOI: 10.3390/su4091946