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Stirring digital innovation in wood waste upcycling: system dynamics as a circular design decision-making methodology

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Abstract. The urgency to reduce climate-changing emissions and natural resources exploitation is pushing architecture and industrial design to explore viable options to innovate current practices on material use. In forest-based industries, in particular, wood upcycling is emerging as a pivotal investigation field, with a specific research agenda aimed at reducing the impacts generated by the rising demand of timber products and the actual incineration and landfilling rates. Indeed, the development of new technological solutions needs to account for energy and material flows, as well as for the environmental impacts and social and economic dynamics. Such a new complexity pushes towards a design approach that links digital technologies to circularity goals for a more comprehensive understanding of the forest-based resource management and the evalutation of alternative scenarios.
In this paper, we propose System Dynamics (SD) as a methodology to provide a qualitative and quantitative framework to promote digital circular innovation in the wood industry.
SD is a dynamic, multi-scale, multi-dimension and site-specific decision-making support tool wich helps designers, researchers and industrial stakeholders to understand and simulate the dynamic behavior and performances of complex systems within specific time and space parameters. The proposed SD for wood waste upcycling allows to model "stock and flow" scenarios, to simulate and compare the consequences of technological options on the system and to target their development in time- and space-based projections. This study outlines the first advances for the SD application to the Italian wood industry, and examines the consequences of the application of different circular strategies on a "business-as-usual" scenario.

Keywords: System Dynamics, Design of Process, Wood Waste, Upcycling, Resources Management, Circular Economy

1. Introduction

Around 70% of all forest-based resources extracted in the EU is destined to construction and furniture industries and, in the next future, the demand for timber products is expected to grow [1].
To reduce virgin materials exploitation and import, the EU implemented several strategies aimed at increasing recycling rates. Nonetheless, the European Environment Agency (EEA) highlights that only

about one-third of wood waste is currently recycled [2]. A substantial portion of wood waste is incinerated for energy production or, worse, is landfilled, generating leachate, greenhouse gas emissions (GHG), reduced landfill lifespan, and soil wastage.

In Italy, despite a current recycling rate up to 62.7% – in line with the EU targets for 2025 and 2030 – and the production of approximately 2.2 million tons of recycled wood, the industry is still facing a significant dependence on external sources, with a rate of imported timber up to 80% [3]. The reliance on timber imports raises concerns regarding the sustainability and resilience of the Italian forest-based industry, as highlighted by the recent economic crisis. Moreover, extensive timber imports contribute to accelerating deforestation in other regions, resulting in severe damages to habitats and local communities.

Consequently, there is an urgent need to promote sustainable and local procurement strategies to reduce reliance on timber imports and ensure the long-term sustainability of the forestry sector. In this context, research and experimentation of circular practices aimed at preserving or increasing the value of the wood resource – such as upcycling – are emerging as a pivotal investigation field. Within the European Union, wood upcycling currently represents less than 2% of the manufacturing turnover in the furniture sector [4]. For the construction sector, on the other hand, no specific quantitative estimate has been made to calculate the percentage of wood waste upcycling. However, the two primary activities for post-use treatment in this sector are energy recovery and recycling. In the European Union, approximately 50 million metric tons of wood waste were generated in 2020, of which 20 million metric tons were sent for recycling [5]. Nonetheless, innovative approach are experimenting with new practices for reusing and valorizing wood waste, leveraging digital design and production technologies such as artificial intelligence, computational design, and digital fabrication, with the aim of transforming wood waste into higher-value products while simultaneously promoting sustainability and conservation of forest resources.

However, to achieve significant impact, the development and implementation of new technological solutions must grapple with the growing complexity of forest resource management scenarios. This complexity involves in-depth analysis of energy and material flows, as well as environmental impacts and socio-economic dynamics. Such a challenging complexity requires an interdisciplinary approach that integrates knowledge from various disciplinary areas, including engineering, environmental and social sciences, and information technology.

Therefore, this study proposes the adoption of System Dynamics (SD) as a methodological framework to comprehensively address both qualitative and quantitative aspects of circular innovation within the wood industry. SD models are widely recognized for their efficacy in delineating and simulating the dynamics of complex systems across defined temporal and spatial dimensions. Further, these models offer an analytical mechanism, often referred to as a “causal loop,” enabling the highlighting of the interwoven environmental, economic, and decision-making influences. Acting as a dynamic, multi-scalar, multi-dimensional, and site-specific decision support model, SD equips designers, researchers, and industrial stakeholders with the tools to comprehend and simulate the dynamic behaviors inherent within intricate systems. Employing SD for wood waste upcycling facilitates the articulation of “stock and flow” scenarios, thereby allowing for the simulation and comparative analysis of technological interventions and their feedbacks on the system dynamics.

This manuscript delineates the initial strides towards the adoption of SD within the Italian wood industry, aimed at examining the “ramifications” of different circular strategies within the confines of a conventional operational system. The integration of such a systemic approach fosters the understanding of the manifold dynamics governing the wood industry and presents an outlook for addressing emergent challenges tied to sustainable resource management and waste mitigation.

The study is framed within the FoRWARD - Furniture Waste for Circular Design research project (MICS – NextGenEU, PE11, Spoke 4), 2022-2025, coordinated by Prof. Massimo Perriccioli and Prof. Marina Rigillo (Department of Architecture, University of Naples “Federico II”), and promoted by the Department of Architecture, the Department of Social Sciences, and the Department of Law,

University of Naples "Federico II" (IT), the Department of Engineering of the University of Palermo (IT), and the Department of Agricultural, Food, Environmental, and Forestry Sciences and Technologies of the University of Florence.

The paper is structured into four sections, including the introduction. The "Materials and Methods" section (2) explores SD and is further segmented into three sub-sections: "SD Approach", "SD General Methodology" and Integrating SD within Wood Resources Management". There a comprehensive exposition of the fundamental principles and methodologies of SD is presented and the application of SD principles and methodologies is examined according to their efficacy and potential benefits in fostering sustainable management practices concerning wood resources. The third section, "Test methodology", focuses on the Qualitative Model and examines the viability and coherence of the proposed model, emphasizing strengths and limitations by means of qualitative. Finally, in the "Conclusions" (4), the main findings of the research are summarized and critically analyzed. Additionally, potential directions for future research are outlined, with a view to further explorations on the discussed topic to broaden the scope of inquiry within the domain of wood resources management leveraging SD principles.

2. Materials and Methods

2.1. SD Approach

System Dynamics (SD), a subfield of systems thinking [6], represents an analytical methodology aimed at studying the dynamic behavior of systems over time, examining how they adapt to or benefit from external influences.

This approach is defined as: *"A branch of control theory which deals with socio-economic systems, and that branch of management science which deals with problems of controllability"* [7].

The development of SD modeling provides a process-oriented dynamic framework for understanding the interactions among interconnected subsystems of complex systems. Initially conceived to examine and understand the dynamic behavior of industrial and urban systems in the 1960s [8, 9], SD has become, over the past 50 years, a consolidated methodology used in a wide range of practical and scientific fields, including management, ecology, economics, education, engineering, public health, and sociology [10]. This approach facilitates the identification and holistic understanding of problems, causes, and influences within complex systems, capturing feedback loops and providing insights into potential system perturbations, making it valuable for sustainable resource planning [11]. Furthermore, through the integration of qualitative and quantitative models, it is possible to obtain a deeper understanding of problematic system behaviors, their root causes, and proposed solutions, allowing for a more comprehensive view of system dynamics [12, 13]. This holistic approach, focused on identifying and characterizing the main feedback loops among various subsystems, such as ecological, environmental, socio-economic, and political ones, facilitates a comprehensive understanding of interactions within the system, enabling more effective and informed resource management and environmental impact assessment and providing a solid foundation for strategic decision-making. Additionally, it offers a significant advantage in its ability to facilitate the conceptualization of multidisciplinary models, providing a range of qualitative tools to complement quantitative simulations [14]. SD models are designed to accurately predict the future behavior of the system, enabling a more comprehensive understanding of internal system interactions and facilitating more effective and informed resource and environmental impact management.

2.2. SD General Methodology

SD methodology adheres to a systematic approach characterized by distinct methodological phases for constructing and analyzing models. Initially, a comprehensive elucidation of the real system ensues, coupled with a precise delineation of the problem under examination. Then, the aims of the model are articulated, delineating specific objectives to be accomplished through its implementation. The definition of the modeling scale follows suit, which entails the specification of temporal and spatial boundaries alongside crucial input-output parameters.

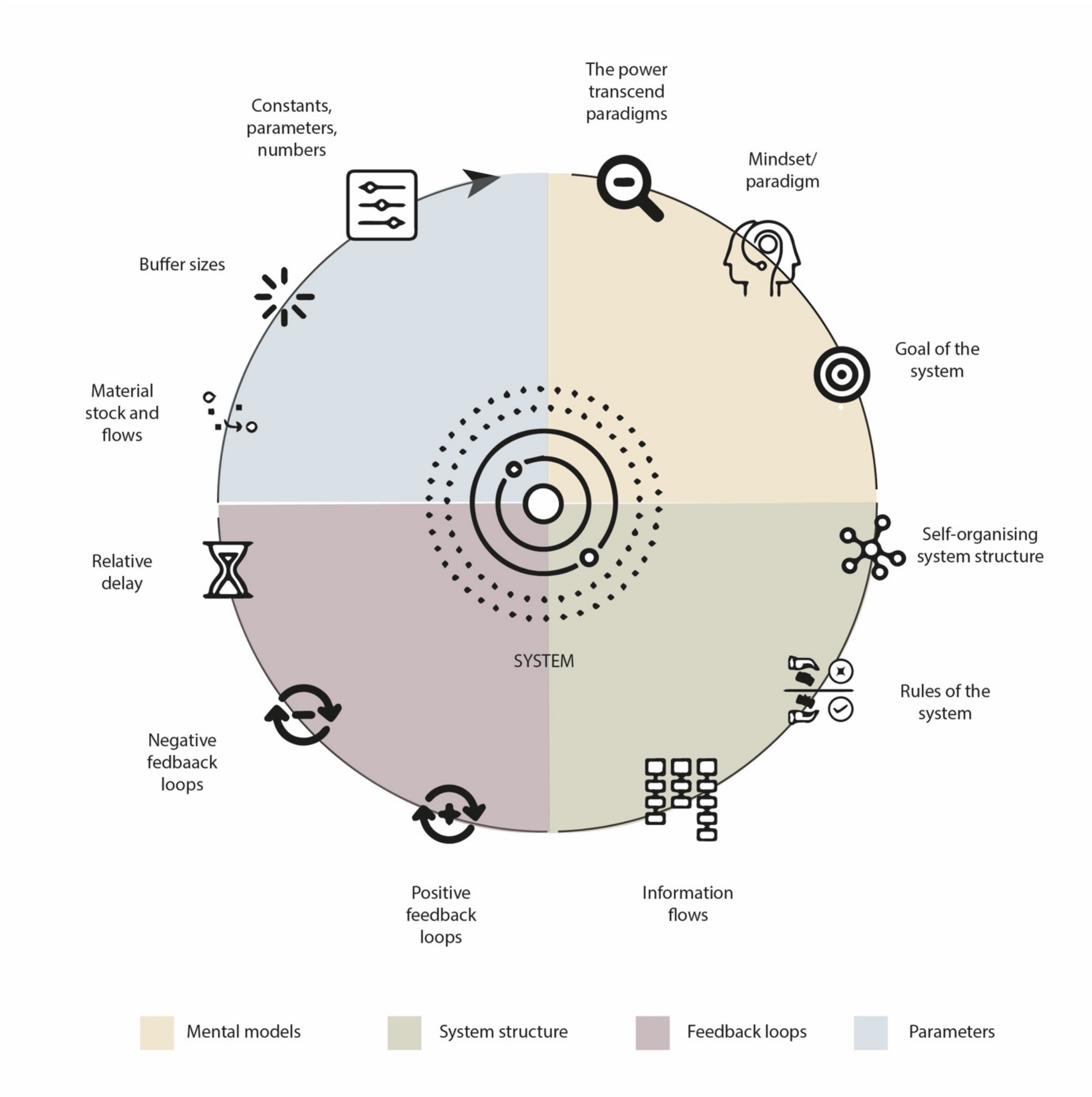

Figure 1. SD methodology. Revised from: Peter Slattery and Stefan Kaufman, How systems thinking compliments behavioural approaches in solving complex problems, Monash University, Australia

Following this, the model is verbalized ("verbal model"), i.e. it is manifested in a narrative exposition aimed at elucidating conceptual underpinnings and pivotal relationships within the system. Consequent to verbalization, system elements are meticulously defined, encompassing state variables, fluxes, and parameters that exert influence over system dynamics. The modeling endeavor progresses to delineate the system's structure and intricate interactions among its components, duly represented in graphical form. During this phase, the identification and graphical representation of feedback loops through causal loop diagrams (diagrams that show interactions among system variables, Table 1) are carried out, highlighting the positive and negative relationships between the variables involved in the system. Mathematical formalism governing system dynamics, encompassing equations and units of measurement, is subsequently established. The model is then concretely visualized through diagrammatic representation, elucidating its architecture and interconnections. Employing dedicated SD simulation software, e.g. Stella, Vensim, Simile ecc. the model is programmatically instantiated. Empirical validation of the model is conducted, entailing rigorous scrutiny against real-world data to validate its behavior. Finally, numerical simulations are undertaken to scrutinize SD under varied conditions, affording prognostic insights into its prospective trajectories.

Table 1. Description of main SD vocabulary

Concept	Description
Causal Relationships	At the heart of system dynamics models are reinforcing and balancing relationships. Reinforcing relationshios imply an increase/decrease in one variable leading to an increase/decrease in another, while balancing relationshio indicate that a change in one variable causes an opposite change in another.
Causal Loop Diagrams	These diagrams graphically capture the relationships between subsystems, revealing feedbacks and time delays. They show interactions among system variables, representing both positive (reinforcing) and negative (balancing) relationships.
Feedback Loops	There are two types of feedback loops: balancing loops, which seek to reduce the discrepancy between the current state and the desired state, and reinforcing loops, which highlight continuous growth or decline trends.
Stock-and-Flow Diagrams	These diagrams represent the accumulation or depletion of resources in the system and the flow of quantities through it. They help understand how resources vary over time and how activities influence this process.
Stock (level)	An accumulation of quantities in specific locations or conditions in a system. A component of a system that accumulates or drains over time. Stocks are the memory of a system and can only be changed by flows.
Flow (rate)	The movement of quantities between stocks within a system boundary or across the model boundary and thereby into or out of the system (sources and drains); changes in stocks over time. Flows represent activity, in contrast to stocks, which represent the state of the system.
Parameters	Constant factors in relationships in a model.

2.3 Integrating SD for Wood Resources Management

Digital Technologies are revolutionizing wood waste upcycling practices, offering new opportunities for dynamic interaction between digital processes and materials [15]. The integration of computational design and digital manufacturing opens new avenues for modeling complex conditions and dependencies within the wood upcycling system, enabling the creation of geometric solutions and detailed rules-based optimizations for material recovery and reuse [16,17]. This approach facilitates a reintegration of traditional knowledge into the upcycling process, transcending barriers between nature and technology, craftsmanship, and industry [18,19]. The transformations induced by digital technologies delineate a shift from consolidated objects and standards to systems focused on the flow of information and interpersonal connections. This new context entails a transition from linear processes to hierarchically structured networked systems and from static technologies to interactive, omnipresent, and dynamic devices [20]. However, to fully realize this objective, a reassessment of current architectural practices is necessary [21]. The traditional linear workflow must be replaced by a circular and holistic one, where all involved actors - clients, architects, engineers, contractors, and suppliers - collaborate from the early stages of the design process, considering the natural form of wood and its potential irregularities [22]. Process design and technology play a crucial role in this context, not only through the utilization of sophisticated tools but also, and importantly, in the ability to manage heuristic processes that blend imagination and innovation. Utilizing SD to develop a dynamic model for controlling, sizing, and managing the wood supply chain entails applying a form of ecological intelligence that employs a holistic and ecosystemic approach. This enables a localized and specific response to environmental and economic challenges, rather than a global and general one.

The primary objective of this study is to analyze how the application of circular approaches to wood waste supply chains can optimize this resource, promoting SD as a methodology to provide a quantitative-quantitative framework for digital and circular innovation in the wood industry. Through the analysis of simulated scenarios, the model aims to evaluate the impact and benefits resulting from the implementation of such approaches on maximizing forest resource utilization and overall wood supply chain management. This approach provides a conceptual and analytical basis for the development and evaluation of effective strategies to optimize the wood supply chain and reduce environmental impacts associated with waste management. The use of SD for wood waste upcycling would enable the modeling of “stock and flow” scenarios, simulate, and compare the consequences of technological options on the system and guide its development in time and space-based projections. A key aspect of this process is the ability to integrate complexity along the entire supply chain, integrating forest management, carbon emissions balancing, and automated geometric processing with the aim of connecting the wood resource with architectural outcomes, creating an integrated and sustainable system.

3. Test Methodology

In order to describe the verbal model and define the elements of the system, it is necessary to study and reconstruct the entire wood supply chain, from sourcing to end-of-life, in its current linear form. Recent studies suggest that the success of sustainable management of supply chains depends on the approach adopted by each upstream and downstream part of the supply chain [23, 24].
Within the broader context of techno-cycles, this model investigates the processes of reuse, redesign, and upcycling of existing resources, aimed at maximizing the value of products and materials throughout their lifecycle, ensuring continuous utility. The qualitative model developed is employed to understand current trends in the supply chain and wood demand, as well as to develop scenarios that integrate sustainability into the construction and furniture sectors.

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Following the reconstruction of the current scenario, processes of reuse, redesign, and recycling are integrated into the supply chain (Fig. 1) to observe what impact these processes have on the entire supply chain and how managing this system over time can facilitate a reduction in resource consumption and impacts. Therefore, the verbal model for the wood supply chain highlights the dynamic interaction between the sourcing - production (I and II) – use and end-of-life phases of the material, considering the influence of environmental and climatic aspects (e.g., transport, emissions, and CO2 sequestration) for the analysis and optimization of the overall benefits derived from the introduction of circular actions (reuse, redesign, upcycling) into the system. Recent research further emphasizes the supply chain as the integration of green into product design and the supply chain to reduce, reuse, recycle, and incorporate clean innovations with a more proactive implementation vision. Connecting the diagram to the provided information allows for the creation of a coherent and logical framework that reflects the model's objective and the complexity of the supply chain in question, with particular attention to circular and sustainable resource management aspects. Consistently with the model's objectives, the system elements diagram integrates circular processes such as reuse, redesign, and recycling into the supply chain diagram. This aligns with the circular approach intended to be studied in the model to understand how these processes influence the entire supply chain and reduce environmental impacts.

The key variables and their underlying causal relationships within the diagram were therefore defined based on the production chain phases (Fig.2), as follows:

1. Harvesting Process. Forestry Cultivation and Management
2. I Processing Process. Wood Processing
3. II Processing Process. Material and Product Production, Distribution, and Trade.
4. Design and Construction Process. Design and Usage.
5. Maintenance and End-of-Life. Post-Usage Maintenance and Services. Possible restoration or disposal interventions.

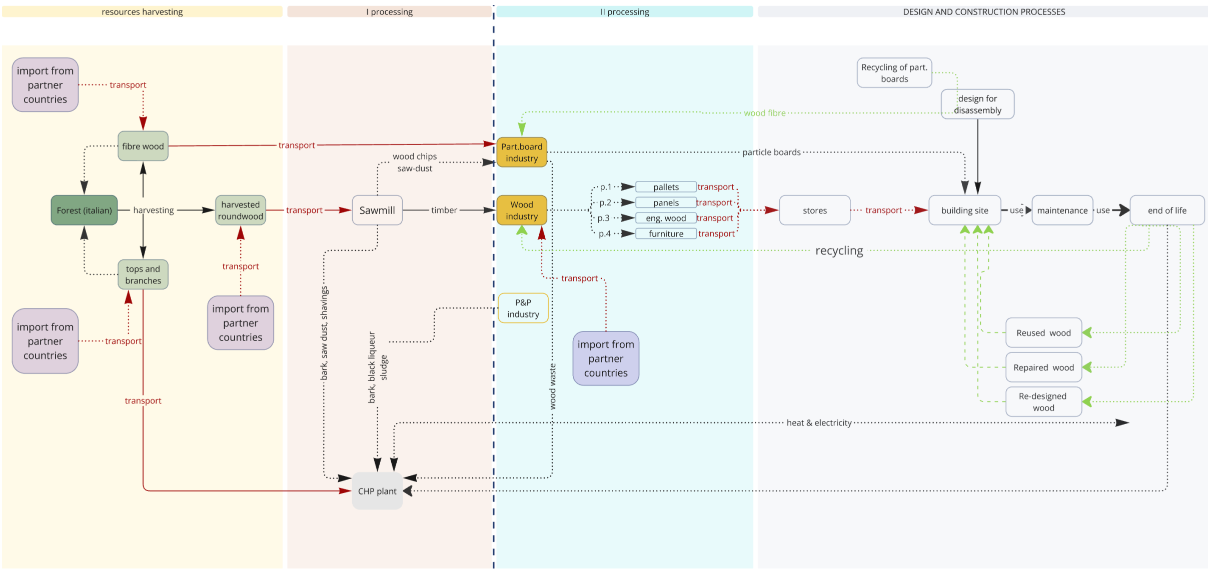

Fig.2 Wood supply chain process diagram in construction. The diagram is divided into 4 phases, marked by the colors yellow-red-blue-gray, which respectively refer to the wood collection phase, first and second processing, and finally to the design and construction phase, with return flows in the case of circular approaches. In purple, material import flows are highlighted, leading to the various phases of the process. In green, stocks related to the forest and harvesting are highlighted. In red, transport flows; in black, current linear flows; in green, circular flows.

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Integrating upcycling operations into the wood supply chain within the proposed model represents a significant opportunity to optimize resources and reduce environmental impacts associated with wood waste management. Upcycling, which involves transforming waste materials into higher-value products, can substantially contribute to maximizing the value of wood resources and reducing the amount of waste destined for disposal.

A possible implementation of the model with a section dedicated to integrating upcycling operations could analyze how these practices influence the system's behavior over time, providing further insights into the dynamics of the wood supply chain and potential implications for management decisions. This approach enables a more comprehensive understanding of interactions within the system and can guide towards more informed and sustainable management decisions.

To assess the qualitative model, a segment of the diagram (Figure 2) is translated into a quantitative model using the SIMILE software. Although the quantitative model is still under progress, it allows us to examine the limitations, challenges, and opportunities of the approach. This initial phase of experimentation involves five stocks:

1. Wood Logs Sawmill Operation (WLSO): Stock resulting from operations carried out to transform wood logs.
2. Sawn Timber (ST): Stock resulting from the transformation of wood logs into forms and dimensions usable for a wide range of projects.
3. Wood Sub Products for Panel Fabrication (WSP for PF): Sub-products of the wood supply chain for panel fabrication.
4. End of Consume (EoC): Stock of wood products in construction that have completed their lifecycle in the building.
5. Reused, Repaired, Remanufactured (3R): Stock resulting from the application of circular processes.

The five stocks correspond, in a simplified manner, to the first and second processing phases, end-of-life, and circular processes of the wood supply chain for construction previously described.

For setting the variables of the influence produced by circular processes (R), it is necessary to determine the availability of raw materials (in a given area) and the quantity of imported semi-finished products. Each flow is therefore influenced by several elements:

1. Availability of raw materials;
2. Quantity of imported processed materials;
3. Number of products to be constructed (directly proportional to the population growth rate);
4. Construction speed.

4. Conclusions

SD modeling emerges as a valuable tool for analyzing and optimizing the complex dynamics of the wood supply chain, thus contributing to the implementation of sustainable strategies in managing and maximizing this resource.

In this work, the challenge of shifting from qualitative to quantitative modeling is undertaken. While SD is proven to be effective in explaining the interaction among different components of the supply chain, including biophysical factors, modeling the socio-economic relationships of the product life cycle and the implications of design choices still poses struggles to a full SD implementation.

Among the impacts identified in this initial phase of experimentation, a significant relationship emerges between closing cycles and the consequent reduction in the average quantity of raw material and product to be extracted and imported. Indeed, the lack of integration of these applications within a broader management system capable of considering both the micro-scale of the product/material and

the macro-scale of urban agglomerations, and gradually extending to the national and global scale, could represent a significant obstacle.
However, this model can be used to simulate alternative scenarios and test supply chain management strategies. Implementing cloud-based collaborative platforms that enable efficient communication and sharing of information among actors in the wood supply chain, including producers, suppliers, distributors, and customers, can facilitate cooperation, reduce delays, and improve transparency along the entire value chain.
The conception or ideation phase in integrated studies on the wood supply chain is argued to be of fundamental importance, as it provides a fundamental understanding of leverage points for sustainable solutions. High-level and qualitative models can be developed relatively quickly and inexpensively to facilitate trend identification and provide insights into the root causes of the multifaceted problems of the wood supply chain, thereby facilitating the formulation of preventive and sustainable solution strategies.
Therefore, throughout the wood lifecycle, it is crucial to promote the use of wood from sustainable management, optimize resource efficiency, reduce dependence on wood material imports, and improve production waste management. Equally important is guiding consumer choices towards circular products, extending producer responsibility systems to increase post-consumer collection, and carefully evaluating incentives for energy use of wood biomass to promote a cascading approach in wood recycling.

Authors contribution

F.P.: conceptualization, methodology, investigation, formal analysis, software, data curation, visualization, and writing – original draft preparation - review and editing. G.G.: conceptualization, writing – review and editing and supervision. F.G.: methodology and supervision. S.R.E.: supervision M.R.: writing – review and editing funding and supervision. M.P.: funding and supervision.
All authors have read and agreed to the published version of the manuscript.

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