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CONCEPTUAL HYBRID MODELING FRAMEWORK FACILITATING SCOPE 3 CARBON EMISSIONS EVALUATION FOR HIGH VALUE MANUFACTURING

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ABSTRACT

Existing manufacturing research on greenhouse gas emissions often focuses on Scope 1 and Scope 2 emissions and underestimates Scope 3 emissions, which are indirect emissions from a firm's value chains, city and region consumption. Traditional methodologies for evaluating carbon emissions are limited for Scope 3 emissions, due to the complexity of manufacturing supply chains and lack of quality data, leading to incomplete carbon accounting and potential double-counting. This challenge is pronounced for high value manufacturing, an emergent manufacturing perspective, due to the complexity of its supply chain network. This study develops a comprehensive hybrid modeling framework for evaluating Scope 3 emissions at product level, useful for manufacturers and modelers.

1 INTRODUCTION

Within manufacturing, there is increasing pressure from government, customers, shareholders, NGOs and other stakeholders to address global warming and global reduction of greenhouse gas emissions to mitigate damage driven by climate shifts (Ellram et al. 2022; George et al. 2016). While there are studies which show that production and energy demands from manufacturing firms significantly contribute to global greenhouse gas emissions (Ritchie et al. 2020), the research uptake in focus on manufacturing is low in comparison to other sectors such as transportation, buildings, agriculture and aviation (Buchenau et al. 2025; Vieira et al. 2024).

Scope 3 emissions, also known as supply chain emissions, value chain emissions or manufacturing emissions constitute the largest emissions within a manufacturing supply chain. These are indirect greenhouse gas emissions resulting from activities that constitute part of the companies' value chains (Dooley et al. 2019; Vieira et al. 2024). Wieland and Creutzig (2025) define Scope 3 emissions, as "the total greenhouse gas emissions generated by the entire network of interconnected and interdependent actors involved in all value-related activities, from upstream to downstream" (Wieland and Creutzig 2025). Scope 3 emissions constitute the highest emissions category within any supply chain, much higher than Scope 1 and Scope 2 direct emissions. For instance, firms participating in a leading carbon disclosure system reported that their Scope 3 emissions were on average, 26 times higher than their Scope 1 and Scope 2 emissions combined (CDP 2024). According to Transport & Environment, a European advocacy group focused on clean transport and energy, studies show that 99.8% of truck manufacturers' total emissions lie within Scope 3 emissions, primarily downstream activities from the use of products that they sell (Transport & Environment 2024). Studies on CO2 emissions by country values show that truckers would be the second highest emitter, if they were a European country (Transport & Environment 2024). Thus, substantial potential for reducing global greenhouse gas emissions lies in reducing Scope 3 emissions.

Broadly speaking, there is an appetite for emissions research amongst stakeholders: in a 7% increase from 2019 to 2021, over 58% of European citizens considered the supply chains of business and industry to be responsible for addressing climate change (European Commission 2021). In the United Kingdom, 90% of manufacturers are aware of carbon emissions categories and targets, while 65% of manufacturers have had to renegotiate their energy contracts in order to reduce their Scope 1 and Scope 2 emissions (MAKE UK 2020), which collectively makes less than 30% of a firm's total emissions (Mervine et al. 2024). Despite these growing stakeholder interests, studies in Scope 3 emissions for manufacturing and high value manufacturing remain limited. However, research on addressing Scope 3 emissions has only recently begun to gain traction within academic research. As observed by Wieland and Creutzig (2025), few articles have addressed the topic within the perspective of supply chain management (Blanco 2021; Hettler and Graf-Vlachy 2023; Vieira et al. 2024). This similar slow traction is evident in important reports by the Intergovernmental Panel on Climate Change (IPCC) which addresses transport, corporate actions and the impact of consumer demand (IPCC 2023).

The complexity of global manufacturing supply chains has been identified as a reason for the paucity of Scope 3 emissions research in manufacturing (Akın Ateş et al. 2022; Franke et al. 2024). In addition, the lack of methodological clarity that appreciates the complexity, data availability, data standardization and supply chain complexity across the upstream and downstream part of the supply chain remains a key challenge in the uptake of Scope 3 emissions studies in manufacturing. This study asks two research questions: What modeling methodologies are employed for evaluating Scope 3 emissions in high value manufacturing sector? And can simulation modeling be designed to effectively evaluate these emissions? We answer these questions by developing a hybrid modeling framework through combining existing modeling methodologies identified from literature.

2 SCOPE 3 CARBON EMISSIONS IN HIGH VALUE MANUFACTURING: STATE OF THE ART

An emerging industrial sector and industrial policy initiative (Bordoloi et al. 2024), "high value manufacturing" (HVM) relates to competitiveness, whereby the firm engages in manufacturing to avoid price competition and (or by) provision of attendant value with the product or service (Livesey 2006; MacBryde et al. 2011; Sminia et al. 2018). Also known as "high integrity manufacturing", it has become the focus of UK government policy that clarifies how manufacturing sectors in high-cost economies are expected to react to increasing global competition, specifically from low-cost economies (Paton et al. 2023; Porter and Ketels 2003). Similar policy initiatives include Industrie 4.0 in Germany, the Advanced Manufacturing Partnership in the USA and the "La Nouvelle France Industrielle" in France (Sminia et al. 2018). While the HVM terminology has "taken its place within the policy and management domain" (Sminia et al. 2018), it is still an emerging research phenomenon. To illustrate this point, we employed the search string, *"high value manufacture*"* in SCOPUS and Web of Science databases and limited our search to "article title" only, examining peer-reviewed articles in journals, conference proceedings and book chapters. This search resulted in 36 articles on SCOPUS and 26 articles on Web of Science, suggesting that HVM has limited academic literature, corroborating an early argument by MacBryde et al. (2013).

HVM adopts solutions like servitization (Baines et al. 2009; Martinez et al. 2008), the enabling of manufacturing processes with real-time data from digital technologies (Kagermann et al. 2013), and the increasing competitiveness and identification of new competitive advantages through the delivery of sustainability and net zero initiatives for the manufacturer (Okorie et al. 2023). Based on this understanding, the literature categorises the following as HVM products: hydrogen fuel cell car, offering product service system; lighting bulbs (energy), with PSS as circular business model; IT computing and equipment offering product life extension through refurbishment, (Okorie et al. 2021). Literature on HVM suggests that, while very important to UK manufacturing, HVM is an incipient phenomenon (Sminia et al. 2018). Thus, descriptions of HVM in the literature often highlight a single differential mechanism (different from "traditional manufacturing"), which includes product differentiation, business model innovation, digital transformation, the deployment of advanced manufacturing, and servitization (Huaccho-Huatuco et al. 2019; Livesey 2006; Sminia et al. 2018).

Accordingly, the process of shaping HVM is currently taking place which includes a recognition of the supply chain emissions directly linked to HVM. As we could not locate studies investigating Scope 3 emissions in high value manufacturing, we explored the state of the art for studies examining Scope 3 emissions and manufacturing more generally. We used the search strings, "manufactur*" AND ""scope 3" OR "value chain emission*" OR "supply chain emission*" OR "manufactur* emission*" on SCOPUS and Web of Science database and limited our search to "article title" only. Across both SCOPUS and Web of Science we found 19 and 11 documents respectively, emphasizing the nascent nature of this research area. When we expanded the search to "article title, abstract and keywords", we found more peer-reviewed documents across multiple disciplines (engineering, environmental science, energy, business management and computer science), suggesting that the research area is interdisciplinary, despite the paucity of studies.

For example, Tian et al (2025) contributes to the Scope 3 emissions in manufacturing by empirically evaluating the impact of Scope 3 emissions disclosure on manufacturing firm performance and investigating the moderating role of supplier complexity (Tian et al. 2025). Li et al. (2024) takes a management theory and qualitative methodology approach by applying fuzzy set qualitative comparative analysis (fsQCA) understand the carbon emission efficiency of China's manufacturing industry. An earlier study (Liu and Ke 2021) investigates how regulatory policies influence a manufacturer's decision between operating as a marketplace or a reseller, and examine the corresponding strategic reactions of its manufacturing partner within a shared supply chain framework (Liu and Ke 2021).

We observe that most of the studies on Scope 3 emissions and manufacturing focuses on two critical categories: providing the theoretical underpinnings for Scope 3 emissions in manufacturing (Hettler and Graf-Vlachy 2023; Patchell 2018; Vieira et al. 2024) and understanding the economics aspects of this research area using manufacturing case studies (e.g. Schmidt et al. 2022; Tian et al. 2025). We also observe that studies in this integrated area were first published in 2004 and have been growing steadily since, with various papers published in Q1 publications (i.e. those in the top quarter of journals by citation). These include, "Transportation Research Part E: Logistics and Transportation Review", "Journal of Cleaner Production", "International Journal of Production Research", "Expert Systems with Applications", "International Journal of Production Economics", "Sustainable Production and Consumption" and "Journal of Environment and Development" amongst others. Finally, all studies we identified offer findings with important insights for manufacturers, policymakers, researchers, government, investors, amongst the identified stakeholders.

3 SCOPE 3 MODELING METHODOLOGY IN MANUFACTURING

Broadly speaking, simulation modeling (also described as "modeling and simulation" or simply, "modeling") has been applied in manufacturing research since the 1950s, allowing researchers to study complex systems which are difficult to research by using traditional theoretical research methods (Zhang et al. 2019). Research objects which are extremely complex, uncertain, and nonlinear, sometimes with quantitative and qualitative, continuous and discrete characteristics simultaneously, are studied using modeling and simulation technology. Within manufacturing, modeling and simulation have been applied to every stage of the product lifecycle (Negahban and Smith 2014; Zhang et al. 2019). These stages include design, production, testing, maintenance, (and other post-manufacturing approaches) procurement, supply, sales, and after-sales service (Zhang et al. 2019). In addition, simulation models are developed to support management decisions about the system due to the closely accurate estimates of the manufacturing system behavior to the actual behavior (Fowler and Rose 2004).

In a recent study, Tolk et al. (2024), describes the categories of modeling and simulation as (a) discrete simulation (where discrete event simulation, finite element methods, agent-based modeling), (b) continuous simulation (system dynamics, continuous simulation, computational fluid dynamics) and (c) quantitative operations research (linear programming, network analysis, dynamic optimization, game theory, queuing theory, Markov processes, decision theory). Other categories include, (d) qualitative operations research (e) socio-ecological research and (f) underrepresented communities and cultures research. Accordingly, modeling and simulation can be a singular or pure modeling approach (for instance, when system dynamics are applied alone (Guo et al. 2023) or as hybrid modeling system (for example, a combination of system dynamics and discrete event simulation (Nalbur and Yavas 2024); agent based modeling and discrete event simulation (Ouda et al. 2023) and system dynamics and agent-based modeling (Nguyen et al. 2024). As most real world problems are complex, requiring different features and characteristics, hybrid modeling is useful as there is hardly one single method ideally suited to capture all these features and optimize their usefulness (Brailsford et al. 2018). A single method may lead to poor solutions, from oversimplification and invalid assumptions, hence the utilization of hybrid modeling approaches.

Within carbon emissions in manufacturing research (and the broader carbon emissions studies), the environmental impacts of Scope 3 have been estimated using the Multi-Regional Input-Output (MRIO) analysis (Martinez et al. 2018). The MRIO modeling is a widely used method for evaluating the environmental impacts of systems and products throughout their entire supply chain (Onat et al. 2014) and shows the interdependencies between regions and sectors within the global economy (Turner et al. 2007; Wiedmann et al. 2007). Hybrid MRIO has been utilized in several studies, for example where inter-provincial physical supply and use tables are integrated with physical MRIO tables (Ye et al. 2022), or MRIO databases with national input-output, trade and environmental statistics (Palm et al. 2019).

Consequently, to identify the modeling methodologies applied to supply chain emissions, we administered this search string within Article title, abstract and keywords on SCOPUS, "Scope 3" OR "Scope 3 emission*" OR "value chain emission*" OR "supply chain emission*" OR "manufactur* emission*" AND "modeling" OR "model*" OR "MRIO" OR "multi regional input output" OR "industry 4.0" OR "digital technolog*" OR "system dynam*" OR "agent-based model*" OR "discrete event*" OR "data analyt*". The first part of the search string captures "Scope 3 emissions" while the second part attempts to capture the modeling technology. This search yielded an initial 296 documents. We restricted the first search string to "Article title", reducing the number of articles to 44. We then examined the articles to identify the modeling technologies, the characteristics, the references, the application areas (Table 1).

4 CONCEPTUAL HYBRID MODELING FRAMEWORK FOR SCOPE 3 EMISSIONS EVALUATION IN HVM

4.1 Hybrid Modeling in Manufacturing Operations Research

Hybrid modeling combines at least two modeling approaches to model complex enterprise-wide systems and its use has grown since 2010 (Brailsford et al. 2018). We find hybrid modeling much developed in Operations Research (OR) as a discipline (Tolk et al. 2021, 2024), but has recently picked up in manufacturing and manufacturing design research (Gnoni et al. 2003; Meade et al. 2006; Mourtzis 2020). In addition, hybrid modeling has increasingly been employed in LCA focused research (Hong et al. 2016; Tennison et al. 2021). To develop a conceptual hybrid modeling framework to facilitate Scope 3 emissions for high value manufacturing, we examine existing hybrid modeling research and their frameworks. In their study, Brailsford, et al. (2018) developed a conceptual framework for hybrid simulation with the aim of capturing the variables identified in their review study as well as providing a structure for a set of good practice guidelines for researchers and modelers. Their framework identifies 4 stages of simulation study: (a) real world problem, (b) developing a conceptual model (c) developing a computer model and from this (d) a clarification of the solution and understanding, which allows for validation and proof of concept implementation (Brailsford et al. 2018). The hybrid modeling study by Tolk et al. (2021) develops a cross-disciplinary conceptual framework that supports the development of new, modular hybrid modeling methods, tools and applications. Consequently, they argue that a hybrid modeling framework must allow for transdisciplinary, interdisciplinary and multidisciplinary research in order to meet contemporary modeling and simulation challenges (Tolk et al. 2021).

Similarly, in their conceptual framework for hybrid system dynamics and discrete event simulation for healthcare, Chahal et al. (2013) proposed a framework based on cyclic interaction between the SD and DES models and parallel interaction of the SD and DES models while information is exchanged during run time Their hybrid model is tested using an explanatory accident and emergency department case study which showed deeper insight of the challenges resulting in better decision-making for medical stakeholders (Chahal et al. 2013). In the longest and most comprehensive accounting of national health-care emissions globally, a hybrid model (top-down economic modeling and bottom-up data) was used to quantify greenhouse gas emissions within Scopes 1, 2 and 3 of the Greenhouse Gas Protocol. For Scope 3, Tennison et al. (2021) captured patient and visitor travel emissions from 1990 to 2019. It was observed that conducting a comprehensive uncertainty analysis (for instance, using Monte Carlo simulation-based analysis) was not feasible due to the hybrid approach combining multiple bottom-up data sets with top-down MRIO results (Tennison et al. 2021).

Table 1: Modeling methods for carbon emissions evaluation as identified in the literature.

Methods	Characteristics for Value Chain Modeling	Application Areas	References
Game Theory	A mathematical framework used to analyze cooperation and conflict that arise from the strategic interactions among intelligent, rational decision-maker. Key functionalities include dynamic and repeated games, information asymmetry, Nash equilibrium and Pareto efficiency, etc.	Social sciences, economics, politics, evolutionary theory in biology.	Bai et al. 2021; Gu et al. 2021; Mahbub et al. 2022; Palafox-Alcantar et al. 2020; Wang et al. 2025; Xia et al. 2024
Multi Regional Input Output Modeling (MRIO) & Lifecycle Assessment	A modeling method using large datasets that quantifies interdependence of different activities, capturing economic interactions between industries and across multiple regions and countries.	Manufacturing, building and built environment, carbon foot printing, transportation, water and energy use.	Turner et al. 2007; Wiedmann et al. 2007
Game Theory & MRIO	Hybrid modeling using game theoretic approach and MRIO offers characteristics such as comprehensive supply chain mapping, policy and incentive modeling, Scope 3 emissions attribution and multi-actor strategic analysis.	Air pollution, energy sector, transportation and logistics, sustainable consumption and production.	Diao et al. 2024; Xia et al. 2024
Game Theory and System Dynamics	Hybrid modeling of GT and SD allows for strategic interaction of decision making and understanding how these decisions affect and are affected by time-dependent feedback loops and delays in the system.	Carbon trading market across local and regional government, Green Technology.	Guo et al. 2023; Qu et al. 2021; Zhang et al. 2019
MRIO and Agent Based Modeling	Hybrid modeling evaluation of macro and micro-level insights. Macroeconomic flows between region and sectors. The hybrid combination allows for multi-scale integration, enhanced Scope 3 modeling, policy sensitive characteristics and temporal-spatial analysis	Flood management, Natural Disasters.	Jiang et al. 2024; Juhel et al. 2024
Discrete Event Simulation	DES modeling has several characteristics useful for carbon emissions modeling, as it is useful for analyzing complex systems where deviations may happen at discrete points in time. Characteristics include, event-driven structure, process-focused representation, stochastic behavior handling, scenario testing capability, granular time resolution, scalability.	Consumer goods, lean logistics, manufacturing retailing systems.	Ugarte et al. 2016; Prajapat et al. 2020

System Dynamics	SD modeling as a tool allows for the understanding, analyzing and forecasting carbon emissions within complex systems and broader economic sectors. Key characteristics includes feedback loops, stock-and-flow structures, time delays, scenario testing.	Dutch chemical manufacturing cluster.	Janipour et al. 2022
System Dynamics and Discrete Event Simulation	Hybrid modeling using SD & DES combines key characteristics such as enhanced value chain modeling. Other characteristics include feedback integration, temporal and spatial resolution, scalability and modularity, uncertainty and sensitivity analysis, visualization and decision support.	Green logistics, Electric Bus Industries, Manufacturing Processes.	Nalbur and Yavas 2024; Onyeje et al. 2024
Environmental Input-Output Life Cycle Assessment (EIOLCA)	A top-down approach used to estimate the environmental impacts associated with economic activities. It integrates environmental data with economic input-output tables. Key characteristics include the wide value chain coverage which are difficult to measure using traditional LCA alone, the inclusion of embodied emissions in goods and services, sectoral and geographic aggregation, data intensity and complexity, flexibility and transparency, as the EIOLCA allows for scenario analysis and evaluation of mitigation strategies.	Automotive manufacturing, FMCG, construction, financial services and built environment, transportation and logistics.	Demeter et al. 2021; Noya et al. 2017; Rama et al. 2021
Hybrid LCA (IO and Process Based)	A hybrid LCA combines macro and micro analysis, providing detailed, product-specific emissions data, capturing upstream, economy-wide emissions using economic input-output tables. It allows for better coverage of Scope 3 emissions, increased accuracy and scalability for upstream and indirect activities. They are ideal for corporate carbon accounting and product carbon footprints.	Manufacturing, FMCG, renewable and non-renewable energy, apparel and textiles, pharmaceuticals and chemicals.	Guan et al. 2016; Jang et al. 2015; Lee and Ma 2013; Wiedmann et al. 2009

4.2 Description of the Proposed Conceptual Hybrid Modeling Framework

From Table 1 and Section 4.1, it can be said that a hybrid modeling and simulation study recognizes the use of interdisciplinary methods and interdisciplinary applications (Powell and Mustafee, 2017). In addition, while conceptual modeling is a vital stage of model development, the uptake of conceptual modeling research in Scope 3 emissions research is yet to fully integrate discrete and continuous simulation (Tolk et al. 2024) with quantitative operation research (such as game theory, network analysis and dynamic optimization) and environmental modeling approaches such as MRIO. The combination of these categories as applied in high value manufacturing presents a complex system requiring the use of interdisciplinary, multidisciplinary and cross-disciplinary methods in the wider simulation study (Tolk et al. 2021).

We propose a 4-phase generic framework for the hybrid simulation as shown in Figure 1, learning from the frameworks from several sources: Chahal et al. (2013), which captures hybrid simulation phases and Tolk et al. (2024) as this captures research methodology categories. Phase 1 of the framework focuses on identifying whether the problem requires a hybrid simulation. There needs to be a clear justification for the use of hybrid simulation, where the complexity of the problem and the system is established (Fahrland 1970). Once it has been identified that the problem requires a hybrid simulation, Phase 2 is carried out to determine the hybrid interactions needed for the modeling using the understanding of the system and an understanding of the modeling categories and their characteristics as captured in Table 1. As this is a "Scope 3" problem one of MRIO modeling, LCA and Hybrid LCA would be required part of the hybrid models, alongside at least one of DES, SD, ABM, Game Theory, etc., as captured in Table 1. Tolk et al, (2024) categorizes these simulation examples as discrete simulation, continuous simulation and quantitative operations research. In Phase 3, we will map the right modeling method which answers the problem. Phase 4 provides clear guidance for mapping between the specific modeling methods. This phase will include identification of interaction points, formulation of relationships, identification of agents, identification of visualization interface, mapping corresponding interaction points between the hybrid models (which includes the environmental modeling).

Start by clarifying the problem and defining the objectives (Figure 1). Once the objectives are clarified and it is certain that the problem requires hybrid simulation, the next step is to identify the right environmental model to use and the right discrete, continuous or quantitative operations research model based on parameters such as data type, input data and characteristics of the modeling type and their usefulness in solving this problem. Several studies provides this information for system dynamics (e.g., Sterman 2000), discrete event simulation (e.g., Robinson 2008a, 2008b), agent based models (Law, 2015) and MRIO modeling (e.g., Oppon et al. 2018) or the use of LCA (Minx et al. 2009).

Defining interaction points for integrated modeling: After identifying the key interdependencies between models, the next essential step is to define the interaction points—critical variables that facilitate data exchange across system dynamics (SD), discrete event simulation (DES), and multi-regional input-output (MRIO) models in a hybrid simulation framework. These points represent both the variables being transferred (replaced or influenced) and those providing the input (replacing or influencing). Since the variables better represented or impacted by another model have already been determined, defining interaction points becomes a matter of systematically pairing these corresponding variables across models. This mapping ensures transparent and coherent information flow, which is fundamental for achieving consistency in integrated simulation analyses and for capturing dynamic feedbacks and dependencies across temporal and spatial scales (Chahal et al. 2013).

We then *define relationships between interaction points.* In a high-value manufacturing context, where precision and dynamic system interdependencies are critical, robust definition of interaction points ensures coherent integration of economic, operational, and environmental dimensions, essential for informed life cycle decision-making. These interaction points or relationships typically fall into three categories: (a) *Direct replacement:* A variable in one model is directly substituted with the value from the corresponding variable in another model during hybrid simulation. (b) *Aggregation/disaggregation:* Although both models represent equivalent interaction points, values are not directly substituted. Instead, system dynamics (SD) variables may be disaggregated for use in discrete event simulation (DES), and DES outputs may be aggregated for input into the SD model. (c) *Causal relationship:* When models do not share equivalent interaction points, one model's variable influences the other through a cause-effect link. These interactions must be clearly defined using mathematical expressions.

Finally, *we align interaction points across SD, DES, and MRIO models*. Effective coupling of SD and DES models relies on ensuring that key variables—termed interaction points—are represented consistently across both Figure 1 and Figure 2 Where relationships involve direct value substitution or structured aggregation/disaggregation, alignment is generally straightforward, as corresponding variables are already mirrored across the models. However, complexity arises in causal interactions, where the influence of one model's variable must be traceable—either directly or indirectly—within the structure of the receiving model. In such cases, careful design is required to embed or approximate the influencing variables to ensure accurate data flow and system coherence, which is essential for robust life cycle integration and impact assessment.

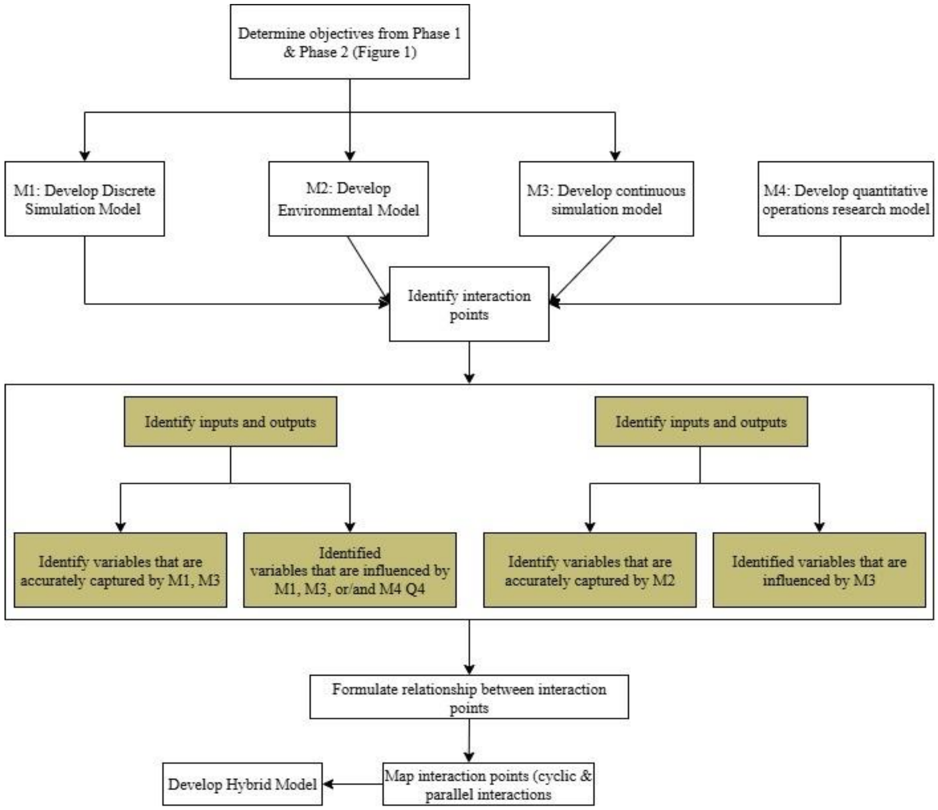

Figure 1: Expanded hybrid simulation framework (with environmental modeling); Adapted from Chahal et al. (2013).

5 CONCLUSION

This paper contributes to the field of modeling and simulation from a hybrid methodological perspective. We propose a stepwise and practical framework for developing a conceptual hybrid simulation model for evaluating Scope 3 emissions in high value manufacturing. Scope 3 emissions, also known as supply chain or value chain emissions, have been under-researched, despite contributing to over 70% of total greenhouse gas emissions for most industries. This study aims to do two things. First, from existing literature, we provide clarity on the hybrid simulation models and their characteristics for Scope 3 emissions evaluation. Second, we address the lack of methodological clarity on combining the simulation methods, whereby an environmental model is the constant modeling tool within the hybrid models. To this end, we review the state-of-the-art literature on combining system dynamics and discrete event simulation models, with MRIO modeling. While the paper achieves these objectives, it has obvious limitations, which include the lack of application and validation of this conceptual hybrid framework. However, by providing detailed characteristics and a conceptual framework, we intend to guide modelers and researchers in evaluating Scope 3 emissions in manufacturing in their development of hybrid models, which is needed to gain insight into complex manufacturing environments.

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