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Participatory and Collaborative Modeling of Sustainable Systems: A Systematic Review

Rajitha Manellanga
Asia Pacific Institute of Information Technology
Kandy, Sri Lanka
rajitham@apiit.lk

Istvan David
McMaster University
Hamilton, Canada
istvan.david@mcmaster.ca

ABSTRACT

Sustainability has become a key characteristic of modern systems. Unfortunately, the convoluted nature of sustainability limits its understanding and hinders the design of sustainable systems. Thus, cooperation among a diverse set of stakeholders is paramount to sound sustainability-related decisions. Collaborative modeling has demonstrated benefits in facilitating cooperation between technical experts in engineering problems; but fails to include non-technical stakeholders in the modeling endeavor. In contrast, participatory modeling excels in facilitating high-level modeling among a diverse set of stakeholders, often of non-technical profiles; but fails to generate actionable engineering models. To instigate a convergence between the two disciplines, we systematically survey the field of collaborative and participatory modeling for sustainable systems. By analyzing 24 primary studies (published until June 2024), we identify common challenges, cooperation models, modeling formalisms and tools; and recommend future avenues of research.

CCS CONCEPTS

• **General and reference → Surveys and overviews**; • **Social and professional topics → Sustainability**.

KEYWORDS

collaboration, MDE, model-driven, model-based, participatory modeling, survey, sustainability, systematic literture review

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1 INTRODUCTION

Sustainability is the capacity to endure [57] and preserve a system's functionality over time [52]. Sustainability has become one of the key characteristics and a major concern in modern systems [39]. An apt demonstration of this trend is the position the European Commission takes in identifying sustainability as one of the two central topics for a resilient European industry within the framework of Industry 5.0 [44]. Expert voices are also calling to action in developing more sustainable systems and engineering methods [56, 78].

Unfortunately, design for sustainability is significantly challenged by the stratified and multi-systemic nature of sustainability [39], i.e., having different meanings at different levels of abstraction and having different meanings for stakeholders of different domains. Various forms of *cooperative modeling* offer a treatment for these challenges. Modeling allows for treating the problem of stratified meanings by the mechanisms of multi-abstraction and multi-semantics [80]. As such, the role of modeling in the analysis and design of sustainable systems is clearly recognized [28]. Cooperation allows for treating multiple meanings by involving a diverse set of stakeholders at strategic points of the design process.

In the absence of sufficiently diverse cooperation, complex endeavors inevitably fail. For example, Nutt [64] reports that about half of policy decisions fail to achieve the desired results as ignored stakeholder knowledge and interests lead to erroneous decision-making. In response to the need for a diverse involvement of stakeholders, *participatory modeling* [51] facilitates a high-level modeling approach, e.g., through systems dynamics [63], in which non-experts and non-technical stakeholders can be part of the decision-making and design process. While the high level of abstraction and informal modeling benefit diversity, they limit the technical depth modeling can achieve, preventing such cooperative endeavors from shifting into an effective *design* phase. The need for combining participatory modeling with a more technical cooperative modeling paradigm for the design of sustainable systems has been clearly articulated before, e.g., by Midgley [60] and Nabavi et al. [63].

Collaborative modeling [36, 46] is a prime candidate to become the cooperative modeling approach required in the design of sustainable systems. Collaborative modeling is a method or technique in which multiple stakeholders manage, collaborate, and are aware of each others' work on a set of shared formal models [46]. While the benefits of collaborative modeling in technical problems have been demonstrated in academia and industry alike, state-of-the-art collaborative modeling techniques are severely limited in their human facets and communication aspects [37], forming a serious barrier for non-technical stakeholders to participate in collaborative modeling endeavors. This, in turn, restricts collaborative modeling to technical problems and limits the potential of collaborative modeling to be applied in sustainability decisions.

There is a synergy between participatory and collaborative modeling that can benefit the design of sustainable systems. Collaborative modeling can support the detailed design of sustainable systems, but it needs to become stakeholder-focused and inclusive

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of non-technical participants. This is an ambition participatory modeling can aid. The need for this convergence has been recognized in participatory modeling too. Basco-Carrera et al. [27] suggest that participatory modeling needs ways to elevate its impact from the level of consultation to the level of design. However, the convergence of the two paradigms is not straightforward. Brocklesby [29] suggests that for many modeling experts, combining "soft" systems thinking (e.g., in participatory modeling) and "hard" systems thinking (e.g., in collaborative modeling) requires a major cultural shift. The goal of this work is to instigate such a shift and converge participatory and collaborative modeling. To this end, we survey the state of affairs in participatory and collaborative modeling of sustainable systems and distill takeaways for the development of the next generation of cooperative modeling for sustainable systems.

Contributions. We conduct a **systematic literature survey** to identify patterns of collaborative and participatory modeling of sustainable systems. Based on our observations, we **recommend avenues of future research** in collaborative MDE.

Replicability. For independent verification, we publish a replication package containing the data and analysis scripts of our study.[1]

2 BACKGROUND AND RELATED WORK

2.1 Collaborative and participatory modeling

Distributed teams introduce challenges to collaboration in terms of processes, project management, artifact sharing, and consistency [61]. These challenges are further exacerbated in the engineering of complex software-intensive systems that require collaboration between stakeholders of highly diverse expertise. Model-driven engineering (MDE) [71] provides stakeholders with techniques for reasoning about the system at higher levels of abstraction than source code. As the combination of collaboration and MDE, collaborative MDE [36, 37, 46] exhibits the traits of both disciplines. The three key dimensions of collaborative MDE [46] are model management, collaboration, and communication. Collaboration features enable efficient teamwork, e.g., through version control (using locking mechanisms [53] or manual conflict resolution [76]), consistency management [43, 77], and model merge [75]. Recent key developments in the field mostly pertain to this dimension, e.g., personalized change propagation and collaboration semantics [74], and real-time multi-level modeling [42]. Communication is, reportedly [37], the most underdeveloped and least researched dimension of collaborative MDE, severely limiting its applicability in convoluted problems, such as design for sustainability.

Participatory modeling responds to these limitations by bringing together a diverse set of stakeholders, often of non-technical backgrounds [51]. A participatory setting is characterized by the cooperative effort of multiple individuals, including domain experts and method experts [51]. Traditionally, participatory modeling has been often supported by physical media, such as whiteboards and multi-touch tables, allowing for agile modeling but less digital and formal artifacts [50]. However, there are noteworthy digitalization efforts in participatory modeling [55] that have shifted this view recently. Two of the key modeling formalisms in participatory modeling are fuzzy cognitive maps (FCMs) and causal loop diagrams (CLDs). FCMs are used to investigate long-term system behavior and assess intervention effects [73]. CLDs capture systems dynamics through feedback loops [70]. Choosing the right tool, method, and formalism impacts the efficacy of participatory modeling. To aid participants and methodologists in the selection, Voinov et al. [83] provide guidance for tool and method selection, aligned with their earlier work [84] on model integration processes.

2.2 Sustainability and its modeling

Brundland [30] defines sustainability as the capacity to "*meet the needs of the present without compromising the ability of future generations to meet their own needs*". Brundland differentiates between three aspects of sustainability: economic (financial viability), environmental (reduced ecological impact), and societal (elevated utility for society and the human). A somewhat more systems-oriented definition is due to Hilty et al. [52], who define sustainability as the capacity to "*preserve the function of a system over an extended period of time*". Penzenstadler and Femmer [67] extend the three Brundtland dimensions with a fourth one: technical sustainability, which describes the ability of a system to be used over a prolonged period. We rely on this unified four-dimensional model [57].

Different dimensions of sustainability require different efforts. Technical sustainability of software-intensive systems is achieved through evolution mechanisms [38], typically approached at the architectural level [82]. Environmental sustainability is often associated with resource recreation and pollution management. For example, Daly's three principles of achieving sustainability [34] demand renewable resources to be used no faster than the rate at which they regenerate; non-renewable resources to be used no faster than renewable substitutes for them can be put into place; and pollution and waste to be emitted no faster than natural systems can absorb them, recycle them, or render them harmless.

Finally, the link between sustainability and digital twins has been explored in great detail lately, e.g., by Fur et al. [47] who integrate different model-driven approaches for the sustainable development of digital twins, and by Bork et al. [28] who recognize the role of digital twins in enforcing sustainability policies but warn about digital twins becoming unsustainable themselves.

2.3 Related secondary studies

Some secondary studies in collaborative MDE that relate to our work are the following. Franzago et al. [46] conduct a systematic mapping of collaborative MDE until 2015, and define the seminal framework of collaborative MDE, covering the three dimensions of model management, collaboration, and communication. This framework, along with the takeaways, are updated later by David et al. [36], covering the 2015–2021 period. The update highlights a strong imbalance among the three dimensions, with communication being severely overlooked in academic research. The same imbalance is identified in a subsequent industry survey [37]. The work also reveals insights about the length of collaborative projects and the involved stakeholder groups, which are shorter and smaller than those in participatory modeling, respectively. These traits, together with the largely ignored communication dimension, mark potential

[1] https://doi.org/10.5281/zenodo.13328774

limitations of collaborative MDE to support the long-running and diverse projects we find in sustainable systems development.

Camarinha-Matos [31] reports that the importance of cooperative methods is well-understood in the modeling of sustainability, but highlights that cooperation, more often than not, needs to be facilitated among non-technical groups. Mohamed et al. [62] survey the applications of MDE in cyber-physical systems (CPS). They identify sustainability as a challenge in CPS and collaborative modeling as a key design method. Surprisingly, the combination of collaboration for sustainability is not recognized, and the pertinent challenges are not reported. The survey of Barisic et al. [26] on modeling sustainability in CPS reports that about half of their sampled studies rely on models of different disciplines. Despite the clear multi-paradigm view on CPS engineering, collaboration is not addressed in the sampled studies. It seems that collaborative modeling needs to be positioned better in the design for sustainability.

3 STUDY DESIGN

Our goal is to understand and classify cooperative (collaborative or participatory) modeling techniques in the development of sustainable systems. We formulate the following research questions.

RQ1. What is cooperative modeling used for in the development of sustainable systems?
By answering this research question, we aim to shed light on application domains, problems, and sustainability development goals for which cooperative modeling is used.

RQ2. What are the typical types of cooperation in the modeling of sustainability aspects of systems?
Specifically, we are interested in the proportion of collaborative and participatory modeling techniques.

RQ3. Which formalisms are used and with what intent in the cooperative design of sustainable systems?
By answering this research question, we aim to understand which modeling formalisms are considered the most appropriate ones to support various sustainability ambitions.

RQ4. Which (digital) modeling tools are used and how in cooperative modeling of sustainable systems?
We aim to understand how users use tools to model sustainability aspects, including modeling intents.

RQ5. What are some of the challenges and limitations encountered in *participatory* modeling?
By answering this research question, we aim to map the areas MDE and collaborative modeling could contribute to.

RQ6. How can collaborative MDE and participatory modeling be aligned to enable better model-based design of sustainable systems?
We aim to elicit leads and requirements for researchers and tool builders to make collaborative MDE more accessible for the modeling and analysis of sustainable systems.

3.1 Search string

We construct the search string from the key concepts of the study.

Cooperative modeling		Sustainability
“collaborative modeling” OR “participatory modeling”	**AND**	sustainable OR sustainability

Initially, we treat the modeling and collaboration components separately, i.e., search for keywords such as “collaborat*” and “modeling” separately. However, we observe the notion of collaboration often pertaining to collaboration between real-life entities (e.g., companies) and not to modeling. Thus, we opt for explicitly searching for collaborative modeling and participatory modeling. We experiment with synonyms of sustainability (e.g., sustainable development and SDG) and observe no difference in the results. We do not consider various specialized notions of sustainability (e.g., energy-efficiency and maintainability) because the potential lack of completeness would introduce threats to validity.

3.2 Search and selection

To identify relevant studies, we employ a combination of automated search and snowballing. The search has been conducted in June 2024. In the following, we elaborate on this process. The relevant figures are reported in Tab. 1.

3.2.1 *Automated search.*

We run the search string on Scopus (in the “Computer Science” and “Engineering” subject areas), IEEE Xplore, and ACM Digital Library. We preemptively remove full proceedings and forewords. Eventually, we end up with **57 candidate studies**.

Screening. We screen these 57 studies by checking whether any of the following exclusion criteria applies. A paper is excluded if it meets at least one exclusion criterion. Exclusion criteria are evaluated based on the *full reference* (title, authors, venue...) and the *abstract* by *both* authors of this report.

E1. No or unclear cooperative modeling technique.
E2. No or unclear sustainability goal.
E3. Other: not peer-reviewed; not English; not available; secondary or tertiary studies; full proceedings; short papers (< 5 pages).

Eventually, we exclude 20 and retain **37 candidate studies** for further quality assessment. We record a particularly high Cohen-κ of 0.832 (“almost perfect agreement”).

Quality assessment. Following Kitchenham and Charters [54], we assess the quality of the studies and include only the ones above a quality threshold. Due to the complexity of the topic at hand, we take a detailed critical stance and *both authors assess* the 37 publications retained in the screening. The following qualities are assessed in each study based on the full text (1 point – satisfactory, 0.5 – acceptable, 0 – unsatisfactory).

Q1. Collaboration goals and techniques are clear and demonstrated;
Q2. Sustainability dimension is clear;
Q3. Modeling formalism (language) is clear;
Q4. Tool is available (developed one or used one);
Q5. Challenges clearly defined;
Q6. Limitations admitted;
Q7. The approach has been evaluated.

We require the following quality thresholds to include a study for the data extraction phase: (i) the study scores above 50%, i.e., at least 4 points; and (ii) the study scores above 0 points in the first four categories. We consider the first four categories crucial in answering the research questions, hence the second quality constraint.

Eventually, we exclude 25 and **retain 12 primary studies**.

Table 1: Statistics of the search and snowballing rounds

Search round	All	Excluded	Included	κ
Initial search				
↳ Screening	57	20	37	0.832
↳ QA	37	25	**→12 (21.05%)**	
Snowballing				
↳ Pre-screening	1 257	895	362	
↳ Screening	362	307	55	0.805
↳ QA	55	43	**→12 (0.95%)**	
Total	1 314	1 290	**→24 (1.83%)**	

3.2.2 *Snowballing.* We apply forward and backward snowballing to enrich the corpus. Forward snowballing is conducted in Google Scholar, by the recommendations of Wohlin et al. [86]. We automate this step through Publish or Perish. Backward snowballing is conducted by the recommendations of Wohlin [85]. We consider potential inclusion candidates based on title and publication venue, as well as the context of the citation. Candidate publications undergo the same evaluation process as discussed above. We stop after one round of snowballing due to the low inclusion rate (0.95%) and the lack of new knowledge newly included papers bring.

Eventually, we process 1257 references. We exclude 895 references in the pre-screening phase based on the full citation. Of the remaining 362 references, we exclude 307 in the screening phase, based on full citation and the abstract (executed by both authors). Of the remaining 55 references, we exclude 43 in the quality assessment phase, leaving **12 additionally included primary studies**.

Thus, we include **a total of 24 primary studies** in the corpus.

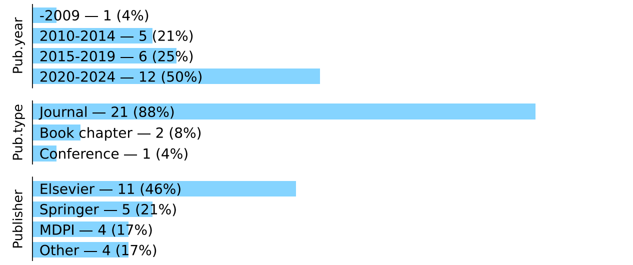
3.2.3 *Threats to validity and quality assessment.* We identify the key threats to the validity of our study, elaborate on the mitigation strategies, and assess the quality of the study.

Construct validity. Our observations are artifacts of the sampled papers. Potential selection bias and missed publications may impact our observations and threaten the construct validity of this study. To mitigate this threat, we employed a diverse selection process consisting of automated search and snowballing [49]. Another threat is the infeasibility of refining sustainability to specific areas in the search string. Not every researcher who works on specific subgenres of sustainability will label their work as such (e.g., papers on energy efficiency or software evolution). Such threats cannot be mitigated and should be accepted as reasonable limitations due to publication practices in sustainability-related areas.

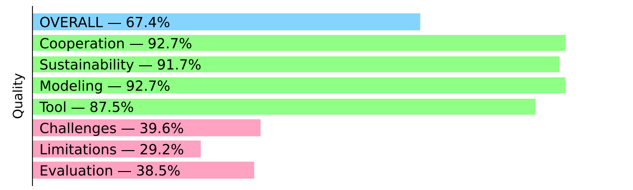
Internal validity. Selection bias may be present in our work due to applying only one round of snowballing. However, the low inclusion rate of 0.95% at the end of the snowballing phase suggests that additional efforts would yield minimal value.

External validity. External validity is concerned with the generalizability of results. Our work focuses on cooperative modeling of sustainability, and thus, the takeaways should not be extrapolated beyond these frames of validity. We mitigate such threats by being explicit about the scope of this study when discussing the reports.

Study quality. Our work scores 63.7% in the rigorous quality checklist of Petersen et al. [68]. (Need for review: 1 point; search strategy: 1 point; evaluation of the search: 2 points; extraction and classification: 2 points; study validity: 1 point.) This quality score is



(a) Papers (as of June 2024)



(b) Quality scores (green: above overall, red: below overall)

Figure 1: Publication trends

significantly higher than the typical values in software engineering—33% median, with only 25% of studies having a quality score of above 40% [68]. Thus, we consider our study of very **high quality**.

3.3 Publication trends and quality

Fig. 1 reports the publication trends in the sampled primary studies.

The number of publications shows an increasing trend in every five-year period from 2009. We record one study from before 2010; and, subsequently, an increasing publication output that culminates in the 2020–2024 period. The past five years account for half of the corpus. About 88% of the sampled studies are journal articles, suggesting mature research our analysis draws from.

The *reporting* quality of publications (Fig. 1b) is moderate, scoring around 67% overall. The overall score is adversely impacted by the limited contextual information about *Challenges*, limited self-reflection and acknowledgment of *Limitations*, and limited *Evaluation* of the approach. However, *Cooperation* (92.7%) and *Sustainability* (91.7%) aspects, as well as *Modeling* (92.7%) and *Tooling* (87.5%) aspects are reported in a particularly detailed fashion.

We judge the corpus to be in a good shape to allow for sound conclusions within reasonable boundaries of validity; but we anticipate limited leads on challenges and limitations (impacts RQ5).

4 RESULTS

4.1 Use-cases and sustainability problems (RQ1)

What is cooperative modeling used for in the development of sustainable systems?

Tab. 2 shows the supported sustainability development goals (SDGs) we encounter in the sampled papers. SDG 6 (Clean water, 17 of 24 – 70.8%) and SDG 13 (Climate action, 18 of 24 – 75.0%) are the dominant problems that are being addressed by some form of cooperative modeling. These two SDGs account for half of all SDGs in the corpus. Specifically, in SDG 6, we see problems such as water management (e.g., mitigation of extreme weather effects

Table 2: Sustainability development goals

SDG		#Studies	Studies
1	No poverty	3 (12.5%)	[9, 16, 17]
2	Zero hunger	5 (20.8%)	[8, 9, 11–13]
6	Clean water	17 (70.8%)	[1–5, 7–9, 13, 14, 18–24]
7	Clean energy	1 (4.2%)	[15]
11	Sustainable cities	2 (8.3%)	[14, 15]
12	Resp. consumption	6 (25.0%)	[1, 8, 15, 16, 19, 20]
13	Climate action	18 (75.0%)	[1–13, 15, 19, 21, 22, 24]
14	Life below water	6 (25.0%)	[6, 10, 11, 14, 23, 24]
15	Life on land	7 (29.2%)	[7, 8, 12–14, 18, 23]
16	Peace, justice...	2 (8.3%)	[14, 23]

Table 3: Number of supported SDGs

#SDGs	#Studies	Studies
1	1 (4.2%)	[17]
2	11 (45.8%)	[2–6, 10, 16, 18, 20–22]
3	6 (25.0%)	[1, 7, 11, 12, 19, 24]
4	4 (16.7%)	[9, 13, 15, 23]
5	2 (8.3%)	[8, 14]

Table 4: Support for sustainability dimensions

Dimension	#Studies	Studies
Environmental	22 (91.7%)	[1–15, 18–24]
Social	18 (75.0%)	[4, 6–20, 23, 24]
Economic	15 (62.5%)	[4, 5, 8, 10, 11, 13–20, 23, 24]

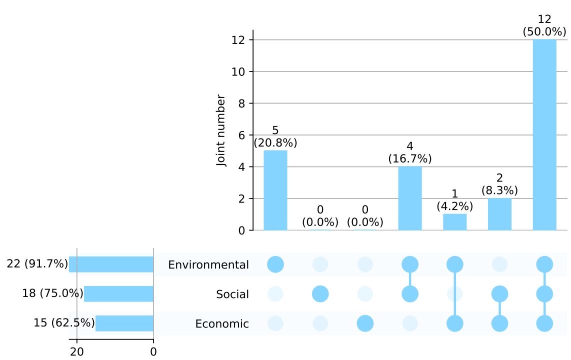


Figure 2: Breakdown of joint sustainability dimensions

on drinking water [2]), flood risk management (e.g., mitigation of harmful effects of climate change [4]), and agriculture (e.g., salinity control of soil in farm lands [7]). In SDG 13, we find problems such as water ecosystems management (e.g., assessing the long-term effects of climate change on coral reefs [6]), and forestry (e.g., improving land managers' understanding of ash tree colonization [12].)

As shown in Tab. 3, most studies target at least two SDGs. The mean number of supported SDGs is 2.75, and the mode is 2.

We frequently encounter the three classical sustainability dimensions of Brundtland [30], as shown in Tab. 4. Similar to the tendency to aim at multiple SDGs, most studies aim at multiple sustainability dimensions. The mean number of supported sustainability dimensions is 2.29, and the mode is 3. A detailed breakdown of joint overlaps is shown in Fig. 2. From this breakdown, it is clear that *environmental sustainability* is the main concern of cooperative modeling, accounting for 5 of 24 (20.8%) studies as a standalone sustainability dimension; 5 of 24 (20.8%) studies in combination with one of the other two sustainability dimensions (4 of 24 – 16.7% together with *social sustainability* and 1 of 24 – 4.2% together with *economic sustainability*); and 12 of 24 (50.0%) studies in combination with both social and economic sustainability—a grand total of 23 of 24 (95.8%) studies focusing on environmental concerns.

RQ1: Use-cases and sustainability problems

Cooperative modeling is primarily used in *environmental sustainability* problems, predominantly *in conjunction* with other sustainability dimensions, typically *targeting multiple SDGs.*

4.2 Cooperation (RQ2)

What are the typical forms of cooperation: collab vs participatory?

Tab. 5 reports the type of cooperation in our sample. Despite using both *collaborative* and *participatory* modeling in the search string, we encounter *participatory modeling* in 23 of 24 (95.8%) cases and only one (4.2%) case of collaborative modeling [22].

As shown in Tab. 6, among the stakeholders involved in the cooperative design for sustainability, we mostly find *domain experts* (21 of 24 – 87.5% of cases; e.g., biologists [13] and agronomists [9]) and non-technical stakeholders (19 of 24 – 79.2%; e.g., government stakeholders [11], NGO representatives [24], resource managers [22], and farmers [23]). Neither of these roles is expected to be a power user of MDE tools. Only a small fraction, 4 of 24 (16.7%) are of a technical background (e.g., researchers [1] and implementers [7]).

As reported in Tab. 7, cooperation is concentrated in the *ideation* phase within the overall systems development lifecycle, with 19 of 24 (79.2%) studies situated in this lifecycle phase. In addition, 3 of 24 – 12.5% cases are situated in the *requirements elicitation* phase; and 2 of 24 (8.3%) cases reach into the *design* phase of systems. One of the two studies focusing on design is the sole case of collaborative modeling, reported in Tab. 5 (Shuler and Mariner [22]).

Table 5: Cooperation type

Coop. type	#Studies	Studies
Participatory	23 (95.8%)	[1–21, 23, 24]
Collaborative	1 (4.2%)	[22]

Table 6: Stakeholders

Stakeholder	#Studies	Studies
Domain expert	21 (87.5%)	[1–4, 6–21, 23]
Non-technical	19 (79.2%)	[1–9, 12, 13, 15–19, 22–24]
Technical	4 (16.7%)	[2, 7, 10, 18]

Table 7: Lifecycle

Lifecycle phase	#Studies	Studies
Ideation	19 (79.2%)	[1–3, 5–15, 17–19, 23, 24]
Requirements elicitation	3 (12.5%)	[4, 16, 20]
Design	2 (8.3%)	[21, 22]

Table 8: Time span

Time span	#Studies	Studies
Long-term	9 (37.5%)	[1–3, 5, 11, 19–22]
Short-term	3 (12.5%)	[7, 9, 16]
N/A	12 (50.0%)	[4, 6, 8, 10, 12–15, 17, 18, 23, 24]

The time span of cooperation varies between a few days and multiple years. Tab. 8 reports the high-level categories of cooperation time spans in the design of sustainable systems development. In studies with explicitly reported time spans, we mostly see long-term endeavors (9 of 24 – 37.5%), as long as 30 years [19] and only a few short-term ones (3 of 24 – 12.5%).

RQ2: Cooperation

Cooperation in the development of sustainable systems is almost exclusively of *participatory* nature, predominantly among *non-technical stakeholders* and *domain experts*, mostly centered around the *ideation phase* of the lifecycle.

4.3 Formalisms and intents (RQ3)

Which formalisms are used and with what intent in the cooperative design of sustainable systems?

As shown in Tab. 9, modeling typically happens through high-level modeling formalisms. We see 12 of 24 (50.0%) of cases using *system dynamics* (SD), often derived from *causal loop diagrams* (CLD), which we find in 11 of 24 (45.8%) cases. The majority of CLD-to-SD transformations are accomplished by mapping CLDs onto stock and flow models to represent systems dynamics, (e.g., [1, 5, 19]). We find cases of *Bayesian networks* (5 of 24 – 20.8%) and *fuzzy cognitive maps* (3 of 24 – 12.5%), which are appropriate choices for cooperative modeling of systems under uncertainty. 5 of 24 (20.8%) sampled studies use traditional *numeric models* without specific support for cooperative modeling. Finally, we encounter a few *UML* models (e.g., class diagrams [12]), 3 of 24 (12.5%) in total.

Tab. 10 reports the modeling intents of cooperating participants. The typical modeling intent in cooperative modeling of sustainability is *quantitative analysis*, in 15 of 24 (62.5%) cases, with a few cases *qualitative* and *other analyses*, e.g., process modeling [8].

RQ3: Formalisms and intents

Cooperative modeling and analysis of sustainability chiefly rely on *systems dynamics* and other system-level modeling formalisms, with the intent of *quantitative simulation.*

Table 9: Modeling formalisms

Formalism	#Studies	Studies
System Dynamics	12 (50.0%)	[1, 2, 4, 5, 8, 9, 14, 19–21, 23, 24]
Causal Loop Diagrams	11 (45.8%)	[1, 2, 4, 5, 7, 9, 13, 18, 20, 23, 24]
Bayesian Network	5 (20.8%)	[2, 3, 6, 10, 11]
Numeric Models	5 (20.8%)	[2, 11, 12, 14, 22]
Fuzzy Cognitive Map	3 (12.5%)	[15–17]
UML and others	3 (12.5%)	[4, 6, 12]

Table 10: Modeling intents

Modeling Formalism	#Studies	Studies
Quantitative simulation	15 (62.5%)	[1, 2, 4, 5, 11, 12, 14, 16, 17, 19–24]
Qualitative simulation	6 (25.0%)	[3, 4, 7, 9, 13, 18]
Other	4 (16.7%)	[6, 8, 10, 15]

Table 11: Type of tools

Type	#Studies	Studies
Simulation	22 (91.7%)	[1–7, 9–12, 14–24]
Drawing	2 (8.3%)	[8, 13]

Table 12: Type of tools by UI

UI	#Studies	Studies
Mixed	17 (70.8%)	[2, 4, 5, 7–10, 12, 14–19, 21, 23, 24]
Visual	6 (25.0%)	[1, 3, 6, 11, 13, 20]
Textual	1 (4.2%)	[22]

4.4 Tools (RQ4)

How are (digital) modeling tools typically used in cooperative modeling of sustainable systems?

Tab. 11 shows the type of tools used in the sampled studies. We mostly see *simulation tools* in all but two cases, i.e., in 22 of 24 (91.7%) studies. In 2 of 24 – 8.3% cases, we find that *drawing tools* are being used. This aligns well with the modeling intents (Tab. 10) being mostly related to the eventual simulation of models.

Tab. 12 reports the type of the user interface (UI) of these tools. We mostly find *mixed* visual and textual UIs, in some cases in some blended fashion. We find that 17 of 24 (70.8%) modeling methods operate through mixed interfaces. One-quarter of tools work exclusively with a *visual* UI, and one tool works with a *textual* UI.

Tab. 13 lists the encountered tools. *Vensim*[2] is the most frequently chosen tool, with 13 of 24 (54.2%) approaches employing it. Vensim is a modeling and simulation software for the design and analysis of causal loop diagrams; in accordance with previous findings about modeling formalisms and intents (Tab. 9 and Tab. 10). Additional three tools—*FCMWizard* (3 of 24 – 12.5%), *Stella*[3] (3 of 24 – 12.5%), and *Hugin*[4] (2 of 24 – 8.3%)—account for one-third of our sample.

[2]https://vensim.com/

[3]https://www.iseesystems.com/

[4]https://www.hugin.com/

Table 13: Tools

Name	#Studies	Studies
Vensim	13 (54.2%)	[2, 4, 5, 7–9, 13, 14, 18, 19, 21, 23, 24]
Stella	3 (12.5%)	[1, 20, 24]
FCMWizard	3 (12.5%)	[15–17]
Hugin	2 (8.3%)	[3, 11]
Other and custom	5 (20.8%)	ArcGIS [6], CORMAS [12], Netica [10], PowerSim [24], custom [22]

RQ4: Tools

Cooperative modeling and analysis of sustainability mostly employs *simulation* tools with *mixed* visual-textual user interfaces, such as *Vensim*, the most frequent choice in our sample.

4.5 Challenges and limitations (RQ5)

We now discuss the recognized challenges and limitations in the cooperative modeling of sustainable systems. The challenges and limitations reported in the sampled primary studies generally pertain to the modeled phenomenon (Sec. 4.5.1), the act of modeling (Sec. 4.5.2), or the socio-political context (Sec. 4.5.3).

We note that challenges and limitations, as well as the evaluation of methods, suffer from quality shortcomings, as reported in Fig. 1. To mitigate threats to validity, we avoid interpretation at this point as much as possible and report only factual information.

4.5.1 Challenges of uncertainty, heterogeneity, and complexity of modeled real-life phenomena. A common theme among the sampled papers is the **complexity** that is inherent to real-life systems, which sustainable system design needs to consider. Some typical examples include modeling water dynamics [2, 22], energy systems [15], biological systems [13], and socio-economic dynamics [17]. These challenges are typically due to the **uncertainty** of physical phenomena [2] that are mostly of **non-linear** nature [15]. A related problem is the **lack of empirical data** [2], which is due to the **heterogeneity of causes** and associated impacts that make it challenging to understand causality [23]. In practical cases, **sustainability dimensions are intertwined** to the level at which the right modeling approach cannot be easily identified [17].

4.5.2 Modeling challenges. We identify two major classes of challenges pertaining to the act of modeling: methodological-technical challenges, and human challenges.

Methodological and technical challenges. Participatory modeling is enabled by sufficiently high-level modeling formalisms that lower the barrier for non-experts. However, on the one hand, **(qualitative) conceptual modeling is often not sufficient** to analyze the complex dynamics of physical, biological, socio-economic, and other natural systems [8]. On the other hand, **refining high-level models to appropriate details** is a complex problem, with typical examples such as the **quantification** of causal loop diagrams [4], and the **parameterization** of simulation models [1].

Optimization for **opposing goals** is an additional challenge, and these optimization challenges often touch upon ethics and humanitarian aspects, e.g., supplying affordable water to consumers while conserving water resources [21].

Finally, **explainability** might be of a concern when black box models are used because of their elevated predictive abilities [12].

Human challenges. Human aspects are magnified in cooperative settings. **Interdisciplinary investigations** are essential in the design of sustainable systems [11]. Yet, the **lack of qualified stakeholders** is often a problem (e.g., [5, 7]). When the number of involved stakeholders is sufficient, modeling *en masse* becomes a problem. **Conflicts among users**, user groups, and uses arise inevitably [20], and maintaining neutrality and transparency in the face of potential conflict in modeling is a problem that **hinders the reconciliation** of differing viewpoints [1]. Especially in cases with cooperative modeling formalisms (e.g., fuzzy cognitive maps), a large number of concepts and weights are assigned by many participants [16], challenging the **scalability of cooperation**.

Finally, some problems require specialized skills, but the **cost of training, software, and salary** of experts might be a problem [22], as well the **lack of technical support** [14].

4.5.3 Socio-political contextual challenges. Finally, there are challenges related to the context within which sustainable systems are developed. It is recognized that without proper political support, sustainable systems cannot be developed and operated at scale [12].

Effective **government regulations are needed** in situations in which design for sustainability is approached through weaker leverage points [59] and as a consequence, the emergent system behavior does not change significantly; e.g., **lack of stakeholder involvement** and adoption [5]. The **lack of political support** from local and federal governments [7, 15], and the **lack of appropriate financial frameworks** [7] are among the key issues.

Stronger leverage points are desired, e.g., by promoting efficient and sustainable behavior of system actors and end-users [21].

RQ5: Challenges and limitations

Challenges in cooperative modeling of sustainable systems pertain to the *complexity of modeled phenomena*, the *methodological, technical, and human* factors of modeling, and the *socio-political context* of modeling.

5 ALIGNING COLLABORATIVE MDE AND PARTICIPATORY MODELING (RQ6)

How can collaborative MDE be aligned with participatory modeling to enable better model-based design of sustainable systems?
To address this final research question of our study, we integrate the findings of our study into a requirement for future collaborative MDE methods and key recommendations.

*Recommendation 1: **Use collaborative and participatory modeling in combination.*** In our sample, we almost exclusively find participatory techniques in support of design for sustainability (Tab. 5), predominantly situated in the ideation and requirements elicitation phases of the overall system development process (Tab. 7). Our observations align with the consensus on the complementary goal and impact of collaborative and participatory modeling, with participatory modeling being associated with the ideation and requirements phases for consulting purposes and collaboration with the design phase for co-design purposes [27].

To leverage this synergy, we recommend researchers of collaborative MDE to focus efforts on end-to-end cooperative support along the development process of sustainable systems by combining participatory modeling and collaborative MDE. Specifically, we call for a more explicit link between (i) requirements elicitation (by participation), and (ii) design (by collaboration). Participatory modeling is an appropriate early step in the design of sustainable systems, but evidence shows [1, 4] that the costs of in-depth technical analysis and the derivation of actionable plans grow exponentially in this paradigm—challenges collaborative MDE is well-suited to tackle.

Contract-based design is an apt method to ensure that key stakeholder constraints are respected in the design phase, with ontologically-grounded variants [81] being particularly suitable to tackle the ambiguous notion of "sustainability".

Recommendation 2: ***Transpose human and communication aspects of participatory modeling to collaborative modeling***. The well-documented shortcomings of collaborative modeling in stakeholder communication [36, 46] form a barrier to the adoption of collaborative MDE [37]. While a participatory phase might take care of the ideation and elicitation of requirements, a subsequent collaborative MDE phase still has to keep stakeholders informed for traceability purposes, especially in the acceptance testing phase.

To support these ambitions, we recommend improving the communication dimension of collaborative MDE [46] and rendering engineered models more accessible to non-technical stakeholders. Recent related efforts in participatory modeling have focused on narrating causal graphs with LLMs [69] and completing reports for participants by generative AI [48]. Additional relevant directions on the collaborative MDE side include multi-view tools [32] with domain-specific notations [45], explanation generation by LLMs [87], and advanced requirements traceability methods [65].

Recommendation 3: ***Transpose advanced model management and collaborative machinery of collaborative MDE to participatory sessions***. Model management and machinery for collaboration are the strongest dimensions of collaborative MDE [37], and must be leveraged accordingly. While most technical developments of collaborative MDE cannot be directly used in participatory modeling, it is important to make strides in transposing them to participatory modeling. Such ambitions are hindered by the clear discrepancy between the rigor of models collaborative MDE tools work with, and the flexible (informal notations) and often analogous modeling (whiteboards, post-it notes) participatory modeling relies on. Informal modeling languages are often invented on the spot by stakeholders with technical acumen, and implemented in tools of convenience, e.g., PowerPoint [35, Sec. IV-A].

Recent developments in MDE aiming to improve flexibility, e.g., blended modeling [41], are important supporting techniques here. We highly recommend continuing the good practice of researching more flexible MDE formalisms, methods, and tools.

Recommendation 4: ***Establish multi-paradigm engineering processes***. We mostly encounter simulation tools (Tab. 11) and simulation intents (Tab. 10) in the surveyed participatory methods. These tools and intents indicate ambitions to go beyond typical non-technical modeling use cases, such as visualization of ideas, and suggest the need for channeling stakeholder input directly to the design phase. Yet, we see high-level formalisms (Tab. 9), which do not allow devising detailed quantitative models (Sec. 4.5.2).

To aid transitions between participatory and collaborative phases, we recommend establishing well-defined processes in support of different cooperation paradigms. Explicitly modeled engineering processes [40] in the presence of automated formalism-transformation facilities [79] are of high utility as they improve the agility of the modeling endeavor. Explicit process models help tame the problem of extended time horizons in the design of sustainable systems through advanced traceability [66]. In our study, we encountered projects that are effective over significantly expanded horizons of 10–30 years [2, 19, 20]. In contrast, the typical length of industry-grade collaborative MDE projects is between 2.5–3 years [37], with nearly 80% of projects ranging up to a maximum of 4 years.

Recommendation 5: ***Natural sciences–informed modeling***. Due to historical reasons, collaborative MDE, in its current form, draws heavily from software-focused modeling formalisms, typically discrete and graph-based ones. In the design of sustainable systems, more complex formalisms from natural sciences are required to be supported. Non-linear relationships reportedly challenge the understanding of causality of natural phenomena [15], which necessitates drawing more from modeling natural systems such as physics and biology. Such problems are more and more often reported, for example, in digital twinning of biophysical systems [35]. Multi-paradigm [80], multi-view [32], and multi-level modeling [25] are readily available to integrate characteristically different modeling formalisms. However, collaborative MDE techniques embracing these paradigms are seldom encountered [42], and have been identified as sought-after ones with moderate research intensity [37].

Furthermore, uncertainty in models has to be dealt with too [2, 23]. The problem of coping with complex models, where a large number of concepts and participants are present, has been well-articulated in our sample [16]. To deal with these challenges, uncertainty has to be promoted to a first principle in modeling [33]. While there exist formalisms that account for uncertainty and non-linearity in participatory modeling, they are sporadically used [72].

Recommendation 6: ***Contextualize systems evolution within "technical sustainability"***. The complete lack of *technical sustainability* (Tab. 4), i.e., the ability to maintain service over a prolonged period of time [52], is one of the key takeaways of our study. This phenomenon is due to two independent factors. First, the evolution of technical systems, especially software systems, such as cyber-physical systems and digital twins, is not recognized as a sustainability problem in the (collaborative) MDE domain. This limitation—which has been corroborated by previous studies [38, 58]—prevents MDE experts from tapping into sustainable design principles and applying the right sustainability-focused mindset when designing complex systems for prolonged usage, longevity, and reusability. Second, the evolution of technical systems is outside the scope of participatory modeling. This shows a lack of involvement of non-technical experts, such as business stakeholders, policy-makers, and government bodies in the design of software-intensive systems. This is a particularly worrisome tendency when considering the growing embeddedness of technical systems into our everyday lives, e.g., in ubiquitous and smart ecosystems [39] in which technical sustainability must be a prime design principle.

We recommend a better contextualization of systems and model evolution in terms of technical sustainability, especially since efficiently addressing the evolutionary needs of ubiquitous smart ecosystems is interlinked with other forms of sustainability, as shown in the case of traditional sustainability dimensions.

Conclusion of RQ6

Our main recommendation is to *use participatory and collaborative modeling jointly* in stronger coupling than currently observed. To achieve this, we recommend transposing the strengths of the two paradigms to each other, and establishing clear, automated modeling processes.

6 CONCLUSION

As sustainability is becoming an increasingly more important characteristic of systems, design for sustainability ought to be better supported by collaborative modeling mechanisms. Without effective collaboration and modeling methods, the complexity of sustainability requirements will keep posing an insurmountable challenge.

We conduct a systematic review of collaborative and participatory modeling for sustainability and report our key findings. We find that design for sustainability almost exclusively runs by participatory modeling, with collaborative MDE being a mere afterthought, despite clearly articulated needs for more quantitative and actionable modeling. A change in the focus of research on collaborative MDE is due in order to enable the MDE body of knowledge for the design of sustainable systems. To instigate this change, we derive actionable pointers for researchers of collaborative MDE.

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