MAIN ARTICLE

Dynamics of interdisciplinarity: a microlevel analysis of communication and facilitation in a group model-building workshop

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Abstract

Participatory system dynamics is assumed to generate inter- and transdisciplinary understanding and whole-system perspectives via scripted workshop structure, facilitation, and the use of visual boundary objects. However, there is little research into how exactly workshop activities and facilitators affect communication dynamics during a workshop and create an interdisciplinary perspective. Thus, we offer an innovative dynamic understanding via a rare microlevel analysis of facilitation and dynamics of communication and interdisciplinarity in a group model-building workshop. We investigate how the conversation focus unfolds over time and examine in depth disciplinary transitions as well as the facilitator's role. We also analyse participants' perceptions of interdisciplinarity from the workshop and provide a research framework for workshop microlevel analysis. Based on the workshop's heritage science setting, we discuss the recursive nature of generating joint meaning and the use of participatory system dynamics for managing interdisciplinarity in a research project and make recommendations.

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Additional Supporting Information may be found online in the supporting information tab for this article.

Introduction and background

Research into important real-world questions often requires approaches, ideas, and skills from more than one discipline. Some fields of research are in themselves inherently interdisciplinary. Such research requires interdisciplinary collaboration. However, despite its importance, interdisciplinary collaboration remains rare (Cairns *et al.*, 2020), as it requires integration of diverse knowledge and worldviews.

Systems research by definition allows for the integration of diverse knowledge. In particular, participatory system dynamics, e.g. in the form of group model building, has been used to understand how different parts of a problem interconnect (Vennix, 1996). The emerging understanding is often captured visually in causal loop diagrams (CLDs) that serve as boundary objects

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(Black, 2013). They represent the 'dependencies across disciplinary, organisational, social or cultural lines' (Black and Andersen, 2012, p. 195). Luna-Reyes *et al.* (2018) show how modelling and simulation artefacts can facilitate interdisciplinary theory building in a group model-building (GMB) context. Thus, system dynamics can help generate a whole-systems perspective, an interdisciplinary understanding of how elements that are studied in different disciplines interrelate and a transdisciplinary understanding of how research is cocreated with practice.

Existing literature has found that participatory system dynamics increases communication among participants, their insights, consensus, and commitment to action (Rouwette *et al.*, 2002; Rouwette *et al.*, 2011; Scott *et al.*, 2016). Thompson *et al.* (2016) also provided initial evidence into which engagement phases generate critical learning incidents at client firms. They found that learning incidents emerge in the model conceptualisation phase and in the confidence-building phase focused on simulation. Yet, it is unclear how such learning comes about during these sessions, how an interdisciplinary or integrated perspective emerges, and how they relate to the activities of the facilitator.

There is guidance available for facilitators in the form of scripts. Scripts are best-practice recipes for how to run a participatory system dynamics workshop. They give good advice for how to structure a workshop and what objectives guide important phases of it, such as variable elicitation, initiating and elaborating a causal loop diagram, etc. They provide a broad overview of the activities of the facilitators (Ackermann *et al.*, 2011; Andersen and Richardson, 1997; Scriptapedia Wikibooks Contributors, n.d.). However, scripts and the broader system dynamics literature still provide rather limited insight into the microlevel of facilitation and communication during the process of generating diagrams.

Outside the system dynamics literature in the area of facilitated modelling and group decision support, several studies report on *microlevel workshop analyses*. These are in-depth studies (e.g. by qualitative research) of workshop *microprocesses*, i.e. the cognitive-communicative-behavioural-material interactions that take place during workshops. Studies of microprocesses are generally concerned with unpacking how facilitated modelling is performed and how it generates outcomes (Franco and Greiffenhagen, 2018; Tavella and Franco, 2015; for a study in a self-facilitated context, see Burger, 2021). They often take a cognitive perspective trying to understand how cognition and actions coevolve (Burger *et al.*, 2018; Tavella and Lami, 2019). Much of this work is grounded in ethnomethodology, the study of people's use of methods (Garfinkel, 1967). Several of these studies also use Tsoukas' (2009) dialogical approach of how new knowledge is created in organisations. These microprocess studies identified successful and unsuccessful facilitation practices and showed how they produce generative, collaborative, or assertive knowledge-production patterns (Tavella and Franco, 2015; Tavella and Papadopoulos, 2015b). Franco and Rouwette (2011) suggested that coding schemes for facilitated modelling can address the

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functions of statements (decision-related, analysis-related), relational or interaction aspects (e.g. group conflict or cohesiveness, social process), and how a model is being used by the facilitator or group members (for examples, see Franco and Rouwette, 2011). While these microprocess studies focus on types of facilitated modelling, they have been applied to the analysis of system dynamics workshops and their outputs such as CLDs to a rather limited extent.

Several exceptions exist in the system dynamics literature. In their paper on facilitated modelling and coding schemes, Franco and Rouwette's (2011) developed a strategy for studying dynamic group processes and included examples from a group model-building workshop. In a Dutch healthcare context, van Nistelrooij *et al.* (2012) analysed power relationships among participating stakeholders through coding of who is being addressed. In a food and farming context in Zambia, Hager, Kopainsky, and Nyanger (Hager *et al.*, 2015; Kopainsky *et al.*, 2017) investigated how participatory SD can be used with audiences without a formal education background. They analysed a workshop transcript, using a framework and coding scheme from interaction and conversation research (Canary and Seibold, 2010).

Other studies focused on the content of the conversation. Dwyer and Stave (2008, see also Stave *et al.*, 2019) conducted an in-depth communication analysis of long-term client engagements, identifying the communication's focus on the problem, its causes, and potential solutions, yet without going into detail on the methods of analysis. For two further client engagements and a student engagement, Herrera *et al.* (2016) and Kreidy (2019) analysed the communication's focus on problem formulation, causes, and solutions as well as the convergent and divergent nature of the conversation. Leaving out all statements by the facilitators, they coded the stakeholder contributions and also reported on changes in participant cognition and attitude.

In contrast, McCardle-Keurentjes and Rouwette (2018) centred their analysis on the facilitator. Focusing on questions asked by facilitators versus chairpersons, they found that, while patterns across multiple engagements varied, facilitators tend to ask questions in a more structured manner, first focusing on rational and social validation and later prompting reflection. Cunico (2017) and Cunico *et al.* (2023) then focused their analysis on facilitators leaving their role and playing the devil's advocate for underrepresented stakeholder groups. Using an adapted coding scheme of content production focused, procedural and decisional interventions, they found that this role change can help address group homogeneity.

Despite these great examples, there is substantial scope for more in-depth understanding of the dynamics of communication and facilitation in participatory system dynamics workshops and for additional work on a framework of how communication and facilitation can be analysed. Such an understanding and framework could contribute to improved practice, both within system dynamics and interdisciplinary research more broadly. This is the gap that this article aims to fill.

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This article aims to deepen our understanding of communication and interdisciplinarity in a participatory workshop environment and how facilitation contributes to communication and interdisciplinarity. The article provides a microlevel analysis, a dynamic view, and thorough understanding of a participatory system dynamics workshop.

Our objectives are to understand:

1. How the disciplinary and interdisciplinary focus of the conversation unfolds over time
2. What activities the facilitator uses to manage the workshop
3. How facilitation affects the conversation

To achieve these objectives, we developed a coding framework for workshop microanalysis and conducted an in-depth qualitative analysis of communication within an interdisciplinary workshop in the area of heritage science. We also qualitatively analysed longer-term effects of the workshop's interdisciplinary communication dynamics using follow-up interviews with the workshop participants. This article thus provides an innovative dynamic microanalysis of the evolution of communication *within* a participatory system dynamics workshop. It offers insights into interdisciplinary communication dynamics and how facilitation supported communication and interdisciplinarity.[1]

Methods: workshop and qualitative analyses

The COMPLEX project

Our engagement was part of the initial phase of the project "COMPLEX: The Degradation of Complex Modern Polymeric Objects in Heritage Collections: A System Dynamics Approach." The project ran from 2017 to 2022. It was placed in the area of heritage science, an interdisciplinary research field applying primarily physical sciences to the study of cultural heritage, such as historic buildings and archaeological or museum objects (Kennedy, 2015; Piñar and Sterflinger, 2021). The COMPLEX project tried to better preserve plastic heritage objects, e.g. if they are part of museum collections. Some historic plastic objects deteriorate within short amounts of time, meaning that research into their degradation is very important within the interdisciplinary field of heritage science. Plastic degradation involves multiple chemical and physical processes influenced by how objects are stored and managed by museums, which interact with each other, interactions which are not well understood. The COMPLEX project thus developed understanding and

[1]Zimmermann and Curran (2020) already provided an extended abstract of this research.

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approaches to model the degradation of modern polymeric materials in museum collections more holistically.

The workshop

In November 2017, we conducted an interdisciplinary group model-building workshop to better understand the interactions between the chemical decay processes of plastic objects and the handling of these objects in museums. The workshop was a kick-off meeting for the COMPLEX project and primarily served the development of a systems perspective and better project management. As the workshop involved stakeholders from research and practice and informed the research project, it might even be classified as transdisciplinary. Yet, we opted for a framing as interdisciplinary in this article because our focus is more on the "museum practice" versus chemical "science" focused interactions during the workshop rather than how it shaped the project. Overall, the workshop included the facilitator and 14 further participants, of whom three were museum professionals, three were permanent academic staff, two were postdoctoral researchers, and six were PhD students. One of the participants was online (for online participation in workshops, see Wilkerson *et al.*, 2020; Zimmermann *et al.*, 2021). Many participants had substantial experience in the field of heritage science, but some were very new to it. Table 1 provides an overview of their disciplinary experience. Three participants were male and the rest female.

The workshop took part at University College London. Nici Zimmermann (NZ) facilitated the workshop and also took over the role of the modeller and process coach (Richardson and Andersen, 1995). Katherine Curran (KC), who was the COMPLEX project lead, served as gatekeeper who had invited the participants and was a workshop participant herself. The workshop lasted approximately from 9:00 a.m. to 2:00 p.m. Its structure is shown in Figure 1 and the detailed agenda with all the scripts is included in Section A in the online supporting information S1. The workshop started with a brief welcome of the gatekeeper and project lead as well as an introduction of the facilitator to participatory system dynamics. Then, in a *graphs over time* session, participants worked in pairs to sketch the past, most likely, feared, and desired future behaviour of the variables they regarded as most important for understanding the decay of plastic objects in museums (for an example, see Figure 2). The facilitator then collected all their variables in a round-robin fashion (*nominal group technique*), asked whether participants considered the variable to be an indicator, driver, or policy variable, and placed them accordingly on a wall of the room. Once finished, each participant was given 12 dots to prioritise the most important variables (*variable prioritisation or dots* exercise). After a short discussion on the starting variable based on the ranking, the *group initiated and elaborated a causal loop diagram*, including graphs over time from the wall as well as further variables when needed (see Figure 3). After a summary from the facilitator, KC drew the workshop to a close.

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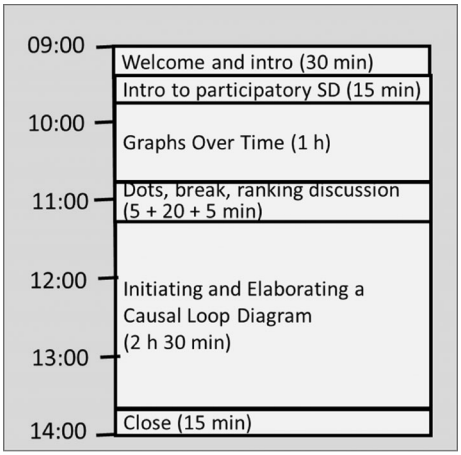
Table 1. Participant categories

Participant categories	Category description	No. of participants	Participants
Museum professionals (M)	Conservators or managers with no particular scientific experience but substantial experience in museum or conservation practice	2	P1, P5
Heritage Professionals with Scientific training (HPS)	Participants with a background in museum or conservation practice and subsequent training in heritage science (This category includes the workshop participant who could not be interviewed.)	3	P3, P8, P12
Scientific Thinkers in Heritage (STH)	Participants with a background in science and heritage science who stretch between science and museum disciplines, but whose scientific background influences their thinking. (This category includes KC.)	4	P6, P7, P10, P14 (= author KC and gatekeeper)
Scientists (S)	Chemical scientists or chemical engineers with no to little experience of working in a museum context whose science background clearly dominates their thinking	5	P2, P4, P9, P11, P13

Fig. 1. Workshop agenda



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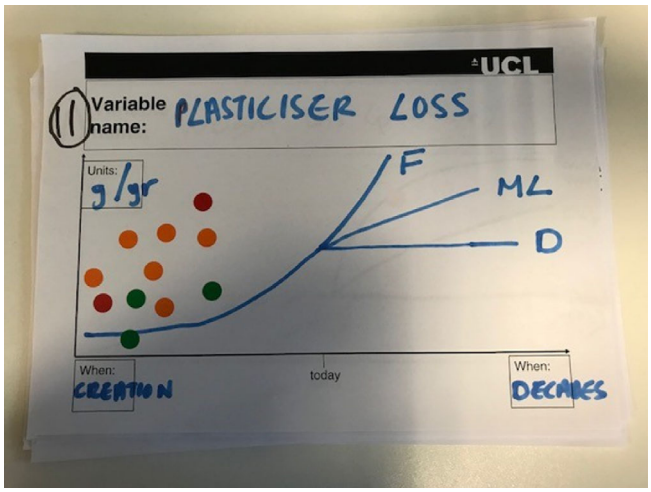

Fig. 2. Example variable with behaviour over time including past as well as feared (F), most likely (ML), and desired (D) future behaviour as well as dots from voting (Curran and Zimmermann, 2022) [Color figure can be viewed at wileyonlinelibrary.com]

Fig. 3. Elaborating a causal loop diagram [Color figure can be viewed at wileyonlinelibrary.com]

Interviews

To capture the long-term effects of the workshop and the retrospective thinking of participants, KC conducted follow-up interviews with 11 of the 13 other participants in June to September 2019. Six second-round

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interviews with a subset of interviewees followed to seek some clarifications. These interviews were carried out in person, with the exception of one interview via Skype and a second-round interview via phone, according to the interviewees' availability. Both authors had jointly developed the rather structured interview guide with questions related to the interviewee's professional identities, their reaction to the workshop and its usefulness, insights, the CLD, language used at the workshop, and interdisciplinary work. These were open and closed questions as well as questions related to workshop photographs or excerpts from the transcript, as shown in Section B in the online supporting information S1.

Data and analysis

The workshop and interviews were audio-recorded, transcribed, and coded. This conforms to previous microlevel workshop analyses, which are based on the coding of individual, several, or fractions of workshops (Franco, 2013; Herrera *et al.*, 2016; Tavella and Franco, 2015; Tavella and Lami, 2019) and of postworkshop interviews (Herrera *et al.*, 2016). For the two second-round interviews not conducted in person, we relied on the interviewer's detailed notes, which were coded as well. Instances that the transcriber found difficult to discern were checked by a second person. In the analysis of these transcripts, we followed best qualitative practice (Kvale and Brinkmann, 2018; Strauss and Corbin, 1998) and innovated on existing practice where necessary. We coded the transcripts in both Nvivo 12 and in Excel 2013. Via a three-phase process, we developed a coding framework for the workshop transcript, fully shown in Section C in the online supporting information S1, capturing:

- The disciplinary/professional background of the speaker and instances where they clearly identify as such
- The topic discussed, i.e. whether it is chemical science or museum practice focused or both
- Transitions between topics
- The physical scale of the topic (molecular, material or object scale and transitions between these)
- Reference to clear mechanisms of cause and effect and model talk
- Clear instances of facilitation

We individually coded the workshop transcript (from variable elicitation to close) and then compared our coding. This first round of coding let us recognise the need for a refined definition of the participants' professional background as well as a way to capture topics that include both a "science" and "museum practice" focus, such as relative humidity. Following these

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modifications, we jointly recoded the workshop transcript and spent much time discussing and resolving any differences in opinion, which often stemmed from our different disciplinary lenses. Thus, our validation method relied on rich discussion and reaching consensus. It conforms to the idea that the benefit of multiple coders is not so much agreement as discussion of any disagreement where the coders act as devil's advocates for one another (Barbour, 2001).

Because of her knowledge of participatory system dynamics, NZ conducted the third phase of coding that involved three additional rounds of coding, focused in detail on instances of facilitation. She inductively added facilitation subcodes to the coding framework and then recoded the entire workshop transcript for not only very explicit but all instances of facilitation. She used inductive coding (before consulting related literature) to give more room to what emerges from the data and her background. KC still acted as a critical friend and sense check to the results. Subsequent consultation of the literature showed that existing coding schemes for the analysis of conversations are not fully appropriate to analyse facilitation (Franco and Rouwette, 2011). Rare coding schemes of facilitation turned out to be not fully appropriate either. Tavella and Papadopoulos (2015a, 2015b) used a coding scheme focused on the facilitator managing the social process (P), managing the content (C), and subjecting substantial expertise (S), a classification that derives from Huxham and Cropper (1994). Yet, the content-focused elements were too aggregated for our analysis and the distinction between process and content somewhat confounded. One study zoomed in very closely to conversational details and analysed how the facilitators' wording encourages reflection and action, but without providing much detail on coding (Franco and Nielsen, 2018). McCardle-Keurentjes and Rouwette (2018) focused exclusively on the facilitator's framing of questions. There is overlap between our, this, and the other frameworks. Yet our framing allowed us to investigate the overlap between asking questions and suggesting representations. In the area of facilitation, our coding framework thus has the following high-level subcategories (for details see Section C in the online supporting information S1):

- Asking
- Directing the discussion
- Explaining
- Reproducing
- Refining and suggesting

The coding of the workshop transcript resulted in 89% coding coverage overall, from start to finish.

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In addition to the workshop, we individually analysed the 11 interview transcripts and six second-stage interviews, each with their disciplinary focus. For example, KC used the participant responses to cluster participants into four distinctive categories, shown in Table 1. NZ coded the interviews for themes related to participatory system dynamics, such as communication and facilitation. During coding, she further developed the analysis into the final coding tree for interviews. Core elements include:

- Communication
- Workshop impression
- Impression of facilitation
- Interdisciplinarity

The entire coding tree is shown in Section C in the online supporting information S1. This resulted in 45% coding coverage on average for the interviews, ranging from a min. of 35% to a max. of 55%, and a 63% coding coverage on average for the second-stage interviews, ranging from a min. of 44% to a max. of 89%. The coding coverage for interviews is lower because not all questions focused on usefulness and impression of the workshop and its communication.

Overall, our analysis benefitted from the very different disciplinary lenses we brought to the analysis of the data. They allowed for rich discussion on our coding as well as our roles as critical friend or devil's advocate.

A framework for workshop microanalysis

In addition to the different disciplinary lenses we brought to coding, we applied different foci to the microlevel analysis of the workshop, e.g. a disciplinary focus to analyse the dynamics of the conversation and a facilitation focus to analyse how the facilitator communicates. While we developed codes fully inductively, as mentioned above, influenced by the disciplinary knowledge of the authors but not by the existing literature on workshop microanalysis, it will be useful to see how they relate. Table 2 summarises diverse foci that are useful in the analysis of microprocesses in a novel framework for workshop microlevel analysis. It includes our own causal, disciplinary, and facilitation foci (in bold) together with the problem-focused analysis by Dwyer and Stave (2008, Stave *et al.*, 2019), the conversation-focused analysis by Herrera *et al.* (2016), the interaction-focused analysis by Hager and coauthors (Hager *et al.*, 2015; Kopainsky *et al.*, 2017), the facilitator-focused analysis by Cunico *et al.* (2023), Tavella and Papadopoulos (2015a, 2015b), Huxam and Cropper (1994), and the question-focused analysis by McCardle-Keurentjes and Rouwette (2018). Detailed subthemes of the disciplinary and facilitation foci are described in Section C in the online supporting information S1. Together, they make three categories. The

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Table 2. Framework for workshop microlevel analysis (with foci used in this analysis in bold)

Content focus		Contribution focus			Facilitation focus		
Problem focus	Disciplinary/ topic focus	Causal focus	Conversation focus	Interaction focus	Facilitator focus	Facilitation focus	Asking/ Question focus
Problem formulation Causal relationships Alternatives/ solutions (development)	**Disciplinary/ professional background of the speaker** **Disciplinary/ topic focus of the discussion** **Transitions between topics**	**Reference to clear mechanisms of cause and effect** Story-like talk **Model talk**	Divergent Convergent Clarifying or summarising Evaluative Negative or dissenting/ disagreeing	Interaction between group members Interaction of participants with the model	Process Content Input of expertise	**Instances of facilitation** **Asking** **Directing the discussion** **Explaining** **Reproducing** **Refining and suggesting**	Rational and social validation Prompting reflection Information management

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content focus includes the problem and disciplinary/topic foci and investigates workshop content. The contribution focus includes the causal, conversation, and interaction focus and analyses how participants' contribute. The facilitation focus includes the facilitator, facilitation, and asking/question focus and analyses the activities of the facilitator.

Not all foci are mutually exclusive. For example, there may be some overlap between *references to clear mechanisms of cause and effect*, *model talk*, and *interaction of participants with the model*. There are similarities between the *facilitation focus* and the *process* category of the *facilitator* focus. The *conversation*, *interaction*, and *facilitator* foci historically build on each other and share many subcodes. We also see some overlap between the *asking/question* focus and the *facilitation* focus, e.g. with questions that serve validation purposes or with the *asking/question focus* being a subcategory of the *asking* category in the *facilitation* focus. Franco and Rouwette (2011) summarise voices in favour of mutually exclusive and exhaustive versus multifunctional and multilevel coding schemes, noting that using multiple coding foci can enrich the dimensions of meaning in facilitated modelling.

Results

In this section we present the focus and the dynamics of communication in the workshop, including how the dynamics relate to participants' disciplinary origin. We also demonstrate the role and activities of the facilitator and how dynamics were triggered by facilitation. Then we present the long-term impact of interdisciplinary workshop communication on participants.

Focus and dynamics of communication

Figure 4 displays the workshop's disciplinary conversation focus, the topic scale, and causal focus of the conversation. The higher focus on chemical "science" topics corresponds to the larger proportion of participants with a scientific background. The conversation focus reveals that, in addition to being focused on chemical "science," "museum practice," and "both," many transitions took place between these topics. The figure also shows the focus on different physical scales of the topic: the object scale that often relates to the storage and handling of a museum object, the material scale of material composition and damage, and the molecular scale of chemical bonds and reactions. Further analyses showed that there were clear disciplinary effects on these scales, with museum and heritage practitioners particularly focusing on the museum object scale and scientific thinkers also emphasising the material and molecular scale. More detail on these scales is presented in another publication (Curran and Zimmermann, 2022). Not surprising for a

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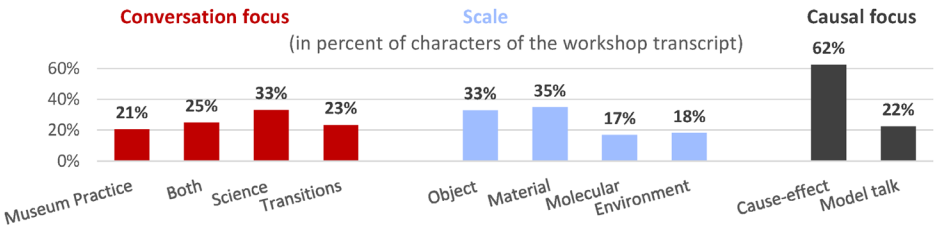

Fig. 4. Focus of the conversation during the workshop (in percent of transcript characters, allowing text to be coded by multiple codes) [Color figure can be viewed at wileyonlinelibrary.com]

system dynamics workshop, the discussion was dominated by references to clear mechanisms of cause and effect. In addition, participants practiced "model talk," i.e. they referred explicitly to the model or what should be represented in it.

A deeper analysis of the disciplinary focus of the conversation, i.e. "museum practice" or "science" focused or focused on "both," reveals that the focus shifted and actually oscillated. Figure 5 shows the dynamics of the conversation, indicating the disciplinary focus of the discussion (chemical "science," "museum practice," or "both") and the category of the speaker (Curran and Zimmermann, 2022). An animated version of Figure 5 is included in online supporting information S2. The welcome session and explanation of system dynamics are left out. During the graphs over time session, approximately from words 2600 to 7000, the disciplinary focus quickly moved between a focus on "museum practice," chemical "science," and "both." As this part of Figure 5 describes the round-robin variable elicitation, it is strongly influenced by the disciplinary spread of people throughout the room.

The causal loop diagramming session started around word 7000 with a topic focus on smell and volatile organic compounds (VOCs), concepts typical for both museum practice and chemical science. After the facilitator's question on "what drives the composition of VOCs in the atmosphere," the conversation moved from a focus on VOCs to a more scientific discussion on the diffusion of substances in materials, indicated by a rather long stretch of the discussion focused on chemical "science" topics from words 8000 to 11,500. It created understanding of the concept of acid diffusion at a much higher level of abstraction than the chemical scientists usually operate in. From words 11,500 to 14,000, the discussion focused on air exchange and related storage and display conditions and thus had a much larger museum-practice focus. It then moved on to a more balanced discussion on light, oxygen, and colour change (words 14,000–17,000) and then a more scientific focus on hydrolysis, i.e. chemical reactions with water, and from there to a scientific discussion on chain scission (words 17,000–18,000). The following discussion on brittleness and cracking as well as plasticiser loss, i.e. loss of softeners, was more balanced. It led to a museum-practice-focused discussion on the treatment and handling of museum objects as well as learning (words

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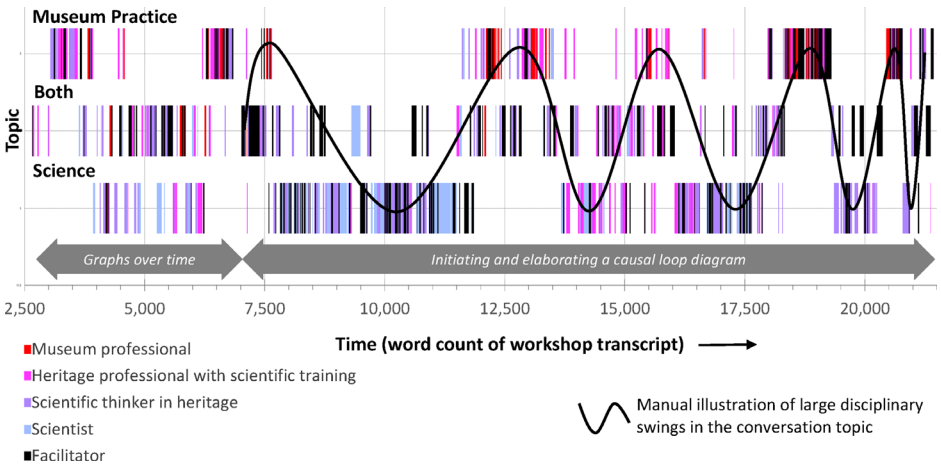

Fig. 5. Dynamics of the conversation, indicating the topic of discussion and speaker category (refined from Curran and Zimmermann, 2022), available in animated form in online supporting information S2

18,000–19,000). Around words 20,000, a short scientifically focused discussion on mass transfer followed, recognising that its mechanics are similar to other chemical processes already on the board. The discussion moved back to a focus on museum practice by discussing resources and value. The resulting CLD is shown as a picture in Section D in the online supporting information S1 and in online supporting information S3 as a Vensim file.

Figure 6 gives a more detailed overview of the evolving topic focus. The facilitator, the project lead, and other participants had active roles in triggering the topic swings. At the start of the causal diagramming session, they were involved in choosing the starting point: the facilitator narrowed the options to the highly voted indicator variables that provide insight into what is going on in the system; participants then suggested colour change, smell, and VOCs, and the project lead confirmed the initial focus on smell and VOCs. After some mapping, a question by the facilitator on "*what drives the composition of VOCs in the atmosphere"* triggered the topic swing to the chemical "science" focus on the diffusion of acids and the related mass transfer (see topic swings 1 and 2 in Figure 6). As the discussion risked focusing on a level of chemical detail inappropriate for the purpose of the workshop and a scientist asked about the level of detail, the facilitator stressed several times in the subsequent conversation the need to remain at a fairly high level of abstraction. She asked the group to "*not go into the absolute detail"* and "*to keep this at the level where it's transferable*," and suggested aggregation. As the quote below shows, a heritage professional with scientific training brought the discussion back to the object level of a film and piece of plastic. When a chemical scientist then related this to the removal of VOCs, a scientific thinker in heritage actively suggested discussing the relation to storage, triggering the next topic swing (no. 3).

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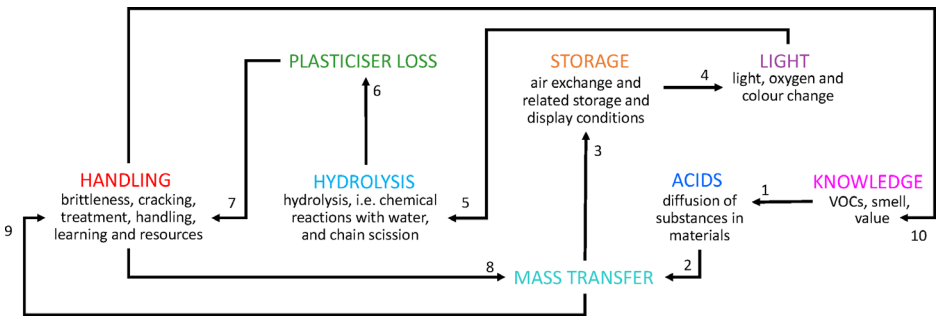

Fig. 6. Evolution of thematic foci during the causal loop diagramming session. The spatial arrangement of thematic foci follows their placement in the CLD. Arrows represent the temporal sequence of large shifts in topic foci. Knowledge topics were starting and ending points of the discussion [Color figure can be viewed at wileyonlinelibrary.com]

So, is a big surface area to bulk, like ratio of that, so like a film would, I suppose, degrade… the migration would be faster… not faster, but I'm thinking more general, rather than the processes, but that would degrade faster than a bigger, bulky piece of plastic, right? [P3,HPS]
Yeah, so you would have a direct relationship with the mass transfer, certainly. [P14,STH]
Surface to bulk ratio, yes? [F]
And then there is also what you are doing outside, either removing the VOCs as they migrate, or is it sealed and they stay there? Is it stagnant, the fluid outside, or are you moving it…? [P9,S]
Ventilation…. [P14,STH]
Then it would be quite nice to get into a little bit of detail into this as it relates to storage, so that could be… [P7,STH]
Yes, because this is what… I guess, do you have to ventilate, or is it better to store it and seal it and keep it stagnant. [P9,S]

The move to light, oxygen and colour change was triggered by the facilitator summarising what had been included in the CLD, drawing the participants to the wall with BOT graphs and asking whether the discussion is moving into the right direction. A heritage professional with scientific training responded that light had not arisen yet, and the facilitator then suggested focussing on it for the next few minutes (topic swing 4). Participant 3, a heritage professional with scientific training, noticed themselves the tendency to focus on detailed chemical reactions.

Yes, we got really bogged down in those, like cellulose acetate and nitrates and the VOCs and we've completely ignored, so far, all the other aspects of it actually, which I think if we did that, eventually, they would all interconnect. But I worry, if we just start talking about chemical reaction, we'll just stay in that one corner,

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whereas there's a whole load of things happening as well that will connect on to it. [P3,HPS]

After a discussion on light, colour change and oxygen, the project lead's comment that "*There's definitely some important chemical processes missing, particularly if we're thinking of cellulose acetate and cellulose nitrate*" and the directly followed question by the facilitator, "*So have we captured this enough, so that we move to those other chemical processes*?" moved the discussion to hydrolysis and then chain scission, i.e. the breaking down of chemical bonds (topic swing 5). The subsequent transitions to plasticiser loss (no. 6), to brittleness and cracking, handling and treatment (no. 7), and mass transfer (no. 8) emerged fluidly based on participants making links.

[Transition to brittleness and cracking:] The consequence you get there is, the number of chain links will have an effect on brittleness and those kind of physical and visible properties. [P14,STH]

[Transition to handling and treatment:] It could be cracking as a consequence of past treatment, so, a solvent-based treatment with lots of glue in construction. [P8,HPS]

[Transition to mass transfer:] Is this really a more surface to bulk ratio problem that if you have more cracks, you have a greater surface to bulk ratio, or a greater surface area, which then feeds into mass transfer which then gives you your plasticiser loss and your water ingress. [P10,STH]

The last transitions occurred with the facilitator asking whether it would "*make sense to go into further detail, or is this enough and you'd rather see whether we have a complete picture captured*" and the project lead's response to focus on "*any other things that people think are missing*." When the discussion briefly moved back to mass transfer, both the project lead and facilitator suggested not going into further detail because the structure for hydrolysis and plasticiser loss would be a parallel of what had been captured for acids. A suggestion by a heritage professional with scientific training then started the final discussion on resources, visitors, value, handling, and treatment (no. 9 and 10), interspersed with adding missing links related to some more chemical concepts.

In the later phases of the CLD-building session, rather than focusing on one topic for a longer period of time, the participants moved back and forth between a chemical "science" and "museum practice" focus increasingly swiftly. The pace of large topic swings accelerated over time, as could be seen in Figure 5. We also observed an increasing focus on the model as such. Figure 7 shows the participants' use of "model talk" over time, indicated by the speaker category. A linear regression line of model talk reveals an

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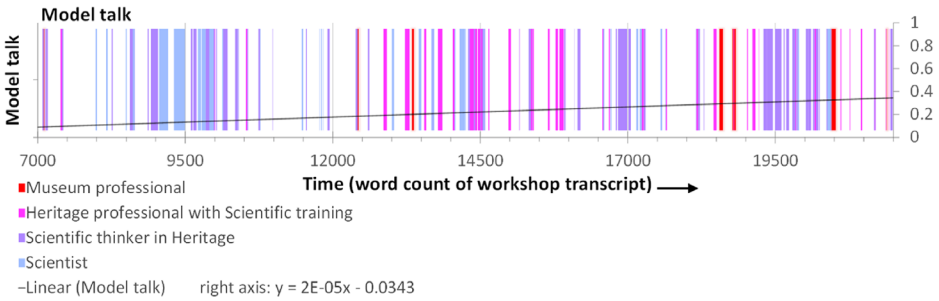

Fig. 7. Occurrence of model talk, indicating the speaker category

increasing trend throughout the causal diagramming session, with participants increasingly referring to the model directly.

During instances of model talk, participants asked, for example, "*[w]hich kind of detail*" *[P9,S]* was desired for the CLD or had concrete suggestions for how to represent certain concepts in terms of aggregation, variable names, and structure:

> *You could change "demand from visitors" to "demand from users" and then underneath that, you'd have visitors and… [P10,STH]*

Increasingly, participants also linked to other elements already present in the CLD:

> *Could we link the temperature with the concentration of the oxygen in the air as well? [P11,S]*

> *I would say that there should be an [arrow] in between, I suppose, brittleness and the object handling policies because the more brittle or fragile the object, the more restrictions there will be on how many people can handle it and what kind of training needs to be undertaken. [P3,HPS]*

The phrase "*the more brittle or fragile the object, the more restrictions there will be"* by P3,HPS reveals an uptake of language typical for system dynamics, which was much exemplified by the facilitator during the workshop.

The analysis of the transcript itself shows that the way participants applied model talk changed not only in terms of frequency but even more so in content. While they had more questions about aggregation in the beginning and suggested how they could represent structure throughout, in the last third of the session they increasingly linked to already existing areas in the CLD. This seems to indicate the increasing disciplinary interconnectedness of the group's boundary object. From the topic swings, some further interesting insights emerge about the

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discipline and role of the people involved in triggering large topic swings as well as the role of the facilitator.

Facilitation effects on interdisciplinary transitions

Facilitation by the facilitator but also by other participants played a role in transitions between topic areas. The facilitator triggered some topic transitions by directing the discussion, asking questions, and by making suggestions. In general, five facilitation activities emerged from the coding process. The facilitator, and others as well, (i) asked questions, (ii) refined and made suggestions, (iii) explained, (iv) reproduced what the group or individuals had said, and (v) directed the discussion by closing topics, opening new ones and commenting on the direction of the discussion. Figure 8 provides an overview of these core activities together with a short explanatory example. In addition and to a lesser extent, the facilitator pointed to feedback mechanisms and the project lead addressed individuals. In particular, asking questions served the purposes of confirmation and clarification, as well as detecting causes and effects. Refinements and suggestions included those about causal connections, variable (names), and how something can be represented in more general terms, e.g. at a higher level of abstraction. Our more detailed analyses showed that when refining and suggesting causality, e.g. as a structural summary of the story the facilitator had heard, this frequently co-occurred with asking the participants for confirmation, i.e. to make sure the structural interpretation represents participants' views. When the facilitator refined or suggested a causality based on what she had heard, in 58% of the instances she also asked explicitly whether participants agree with this; in 10% she asked for clarification and 6% for cause and effect. While most refining and suggesting of causality was based on what participants had said before, a decision was made to code statements as reproducing only if they very explicitly summarised larger parts of the discussion and/or directly mentioned what people had said, for example, as in the quote below.

> *So you are saying that it's not – so that not only the policies affect how much treatment and handling is done, but also the brittleness. So basically, whether I treat or handle an object depends on the brittleness, together with the policies I have about it? [F]*

Some of these facilitation activities are more closely linked to eliciting model structure, such as *asking for* or *suggesting variable names*, *causes and effect, how to represent*, as well as *explaining model structure*. Other activities are indirectly related to the development of the model. For example, if the facilitator *asks for confirmation*, this can happen after a participant has suggested model structure, described a story, if the facilitator seeks final confirmation, or to enable participants to disagree more easily with an seemingly unfit

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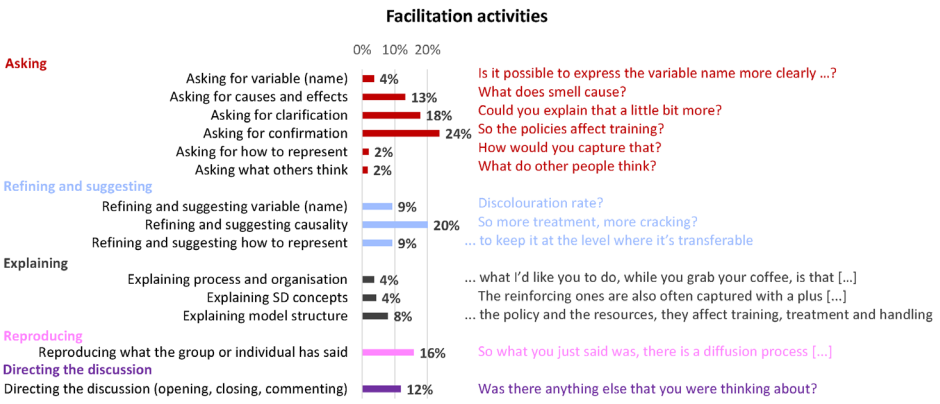

Fig. 8. Core facilitation activities (in percent of references coded as facilitation) and short examples [Color figure can be viewed at wileyonlinelibrary.com]

suggestion. *Directing the discussion* has mixed purposes, such as drawing the group to a new theme, a different level of abstraction, or a different activity.

The instances when either the facilitator or a participant directed the discussion were often related to the large topic swings. The quote below gives an example of how swing 4 from storage to light happened in detail and how both the facilitator and participants were actively involved in directing the discussion.

> *If we can just compare what we are working on with what we have on the wall, I see that some of the things interlink, some of them are also different. You see, we worked a lot on driver variables in the middle, right – we didn't have so many there – but we have captured temperature, for example, we have water, a little bit of humidity also. Do you think we are moving on the centre of the problem, or are we moving on a side-track? [F]*
> *[…]*
> *It's interesting that we haven't brought in light at all. Light is a thing that as a big driver as the objects fade, and a light exposed object is a weakened object, but we haven't captured that at all. [P7,STH]*
> *Yes, we got really bogged down in those […] [P3,HPS]*
> *You seem to find light important, so should we focus on light for a little bit […] [F]*

The above example shows how instances of directing the discussion are a reaction to what happened. The facilitator's deliberate direction of the discussion aimed to step back for capturing a holistic picture. Another example is her question whether it would "*make sense to go into further detail, or is this enough and you'd rather see whether we have a complete picture captured?*" [F], which triggered the last two topic swings. Participants were instrumental in suggesting what is missing and which direction the conversation should take. Participant P7,STH's suggestion "*to get into a little bit of*

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detail into this as it relates to storage" is another example, also highlighting this participant's importance for directing the discussion content, similar to the project lead. Many other instances when either a participant, the project lead, or the facilitator directed the discussion, they did so by taking up a suggestion already made, reinforcing it and asking for the group's agreement, e.g. asking whether the group would find it "*useful then to continue on"* [F] a certain topic. Thus, three motivators for and types of directing the discussion emerged: the aim to step back for capturing a holistic picture, topics perceived as important but still missing, as well as the aim of achieving agreement among the group. These may occur independently or in sequence.

The dynamics of the conversation not only included big topic swings but also the very frequent disciplinary transitions between "museum practice," "both," and chemical "science" foci that Figure 5 showed. About 32% of the transitions were initiated by the facilitator, 4% by participants in a facilitatory mode, particularly by the project lead and another participating academic, and about 64% were independent of facilitation, as shown in Figure 9.

An example of a series of transitions independent of facilitation is shown below, transitioning from chemical "science" to "museum practice," to "both", to "museum practice," and back to "both." It also includes a rare transition from chemical "science" to "museum practice" directly.

> *It's two kinds of Delta E [i.e. colour change], one for the polymer and one for the additive colorants. [P8,HPS, science focus]*
> *You see yellowing/discolouration. [P7,STH, museum practice focus]*
> *Well, you get bleaching, you get yellowing and then you get fading. [P12,HPS, both focus]*
> *So discolouration, a change from the original appearance. [P8,HPS, museum practice focus]*
> *I tend to use discolouration for both bleaching and yellowing and fading, I think it's a blanket term … [P12,HPS, both focus]*

However, these phrases build on what happened before, when the facilitator asked where colour change came from in a "both" focused discussion about colour change. This had led to an inclusion of "science"-focused "*Chemical reactions within the polymer"* [P3,HPS] and further "both"-focused discussion of colour change. It is thus difficult to fully discern statements made with and without facilitation because of the conversation history. With 29% of coded statements the facilitator is quite present throughout. Facilitation interventions that later lead to transitions often take the form of *asking for (further) causes and effects*.

Comparing the conversation focus of the facilitator's with other participants' transition statements reveals quite contrasting foci (see Figure 10). Workshop participants equally draw the conversation to a "museum

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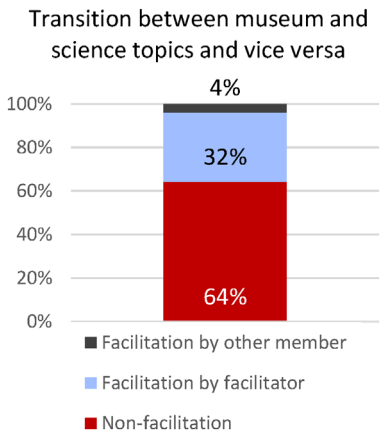

Fig. 9. Transitions between "museum," "both," and chemical "science" topics (in percent of references coded as transition statements) [Color figure can be viewed at wileyonlinelibrary.com]

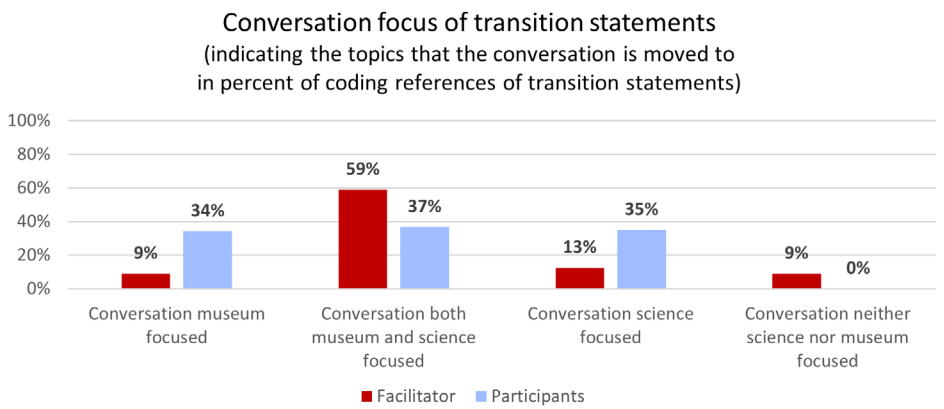

Fig. 10. Conversation focus of the transition statements (in percent of coding references of transition statements). For participants, aggregated numbers across conversation foci exceed 100% because of a long participant statement with a chemical science focus that included variable names clearly relevant to museum practice as well [Color figure can be viewed at wileyonlinelibrary.com]

practice," "both," or chemical "science" focused topic. However, the facilitator has a much higher prevalence of drawing the conversation to a "both"-focused topic. This could reveal the active attempt to involve people and make the conversation relevant to all present.

In summary, we saw that the conversation in the workshop moved back and forth between disciplinary topics. Overall, the pace of shifts between chemical science versus museum-focused stretches of the discussion accelerated over time. The facilitator is responsible for a particularly large proportion of transitions towards a focus on both topics. Yet, the facilitator is not

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responsible for all instances of facilitation; other participants also take important active roles in facilitating the direction of the discussion.

Longer-term effects related to interdisciplinarity

To get a glimpse of the longer-term effects of the interdisciplinary back and forth in the workshop communication and the interdisciplinary linkages in the CLD, we provide a short overview of insights from the postworkshop interviews. We thus present participants' impressions of the interdisciplinary communication and interdisciplinary nature of the CLD.

Concerning the interdisciplinary nature of the workshop, several participants commented that they have not or rarely seen such interdisciplinary meetings.

> *No, actually, this was the first kind of properly interdisciplinary meeting that I had where there was a proper exchange. I've been to a few meetings where there are a large group of people there, but it's usually focused on one aspect and not on trying to figure out the issue as a whole […]. [P10,STH]*

Participants commented that the workshop was "*debatic*" [P11,S], "*focused people to say exactly what they meant*" [P10,STH], and that "*it put the knowledge of everyone at the same level of usefulness*" [P7,STH]. Another participant [P7,STH] mentioned how this created a democratic process, but that it sometimes led to connections between physical and nonmeasurable variables too quickly. Typical insights that participants gained were those into wider and interdisciplinary relationships.

> *It was very interesting to see how different disciplines think on the same topic, how they used different words to describe the same thing and maybe how, as scientists, we try to understand everything through equations, while people coming from a heritage background would try to find something more meaningful to them in terms of their discipline. (P4,S)*

Participants found the CLD useful for understanding such interdisciplinary linkages.

> *I think, without this, the conversation could be derailed, it's like a glue and people would be easy to leave the meeting by saying the scientists were talking about other things and the museum people were talking about them and there is no connection […] [P7, STH]*

> *The systems dynamic model was a new insight for me because I think I've been siloed into VOC analysis for quite some time and then seeing it on a very large wall and all the different things that interact with it, really helped me figure out "okay, there's a lot going on to this, it's not just this one silo." (P10,STH)*

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> *[…] I liked the fact that we were connecting this really in-depth science to storage boxes and display cases and like practical things, and my understanding is that if this is made into the system dynamics model, then you might be able to … see what the relationship is between a change in your opening hours to light damage on… so I think that's why I took it away as a bit of a light bulb moment because, yeah, I could see how they were connecting because this was the big picture, y'know. (P1,M)*

As the workshop largely focused on the better interdisciplinary management of the project, participants also found it useful for their further research in the COMPLEX project or for practice, reporting, for example, that they

> *"Use the picture all the time" in presentations [P10,STH].*

> *I think it helped to focus on what parts of the model needed further investigation and I think that's what fed into the projects that the COMPLEX team have been working on since then. I just remember coming back to the office and my main takeaway was it was connecting the science and why degradation happens and why we see it happen with museum practice, so I just felt like it was the first time that that had really been expressed on one page, that we were connecting museum policy to change in objects which I just thought was really interesting. [P1,M]*

While some participants found it transferable to their work, some also commented that while they enjoyed the bigger picture and found it useful, they kept working in accustomed ways. Others even had difficulties remembering, which indicates limited practical effects on their work.

Thus, overall, participants emphasised their positive impression of the interdisciplinary nature of the workshop and the CLD. It allowed them to see interlinkages in an aggregated way. Transfer into their ways of working was often limited though, especially for the participating PhD students, and seemed largest for museum professionals and the project lead to whom it gave confidence that her team understood the scope and nature of the relevant system.

Discussion

This article analysed a group model-building workshop in the area of heritage science with participants from across museum practice and chemical science backgrounds. The article responds to a lack of research into the microprocesses of participatory system dynamics workshops. It provides a dynamic account of how the conversation during a workshop can move back and forth between disciplinary foci; it analysed these transitions and the impact of facilitation. With few exceptions (e.g. Dwyer and Stave, 2008;

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Herrera *et al.*, 2016; McCardle-Keurentjes and Rouwette, 2018), previous research has focused primarily on the outcomes of participatory engagements (Rouwette *et al.*, 2002; Scott *et al.*, 2013, see also Franco *et al.*, 2021 for a categorisation).

Interdisciplinarity

Our article investigated *how the disciplinary and interdisciplinary focus of the conversation unfolds over time* (objective 1). It showed multiple transitions between the disciplinary and topic foci of the discussion in a GMB workshop (see Figure 5). Through the details of a workshop microlevel analysis, it was possible to understand that there is more than one way that interdisciplinarity can manifest during a system dynamics workshop. Big swings occurred, with phases where a greater museum practice versus chemical science-focus dominated, and much more frequent small transitions where the topic was repeatedly pulled to a focus relevant to both disciplines. When the discussion was focused on one thematic topic such as lighting, frequent small interdisciplinary transitions occurred between a "museum practice," "both," and chemical "science" focus. It allowed discerning the detail of how the different disciplines relate to the CLD produced and potentially to a boundary object more generally.

A second type of interdisciplinarity and transitions existed in terms of big topic shifts, e.g. between storage and light. While these were initiated at one point in time, the detail of such linkages was negotiated and clarified through ongoing conversation that included the frequent small interdisciplinary transitions. Interestingly, the big swings accelerated over the duration of the causal loop diagramming phase. Participants also started to make links to topics already on the wall (see Figure 6). This potentially indicates the effects of a more and more comprehensive CLD that made it increasingly easier to draw connections between a museum practice and chemical "science" focus. It may also be a sign of participants' emergingly coalescent mental model of the system. Participants also increasingly talked in model terms (see Figure 7), by referring to the model, how something can be represented, and using language typical for system dynamics. This reveals an increased familiarity with the task and the concept of a CLD and an emerging use of the CLD as a boundary object for understanding the decay of plastic objects in museums. As participants mentioned, it helped see "the issue as a whole." While the workshop did not have lasting effects on all participants, many highlighted its value in revealing interdisciplinary connections between chemical science and museum practice through the CLD.

System dynamics has been suggested as a useful method for inter- and transdisciplinary research for its helpful philosophical underpinning and tools to capture complex and cross-boundary interactions (e.g. Gallati and Wiesmann, 2011; MacLeod and Nagatsu, 2018; Newell and Siri, 2016). It has

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been used for theory building with researchers from different disciplines (Luna-Reyes *et al.*, 2018), can integrate diverse perspectives (Black, 2013; Luna-Reyes *et al.*, 2021) and helps participants to put themselves into the shoes of the other (see Zimmermann *et al.*, 2015; Zimmermann, 2017). The participatory workshop setting corresponded to a learning situation where participants engage in a mutual feedback process of verbal "gesturing," i.e. making a suggestion based on their personal and subjective experience and receiving other participants' reaction to their "gesture" (Gallagher, 2012; Mead, 1934; Zimmermann *et al.*, 2015; Zimmermann, 2017). From this, concepts and dependencies evolve which are captured as variables and causal relationships in a model on the wall or screen. What happened at our workshop is an example of this process, and the acceleration in the large transitions between the museum and chemical science focus may indicate that via the participatory process and the developing model, participants could make shared meaning of each individual's experiences. This provides a grounding for further work going more deeply into the microprocesses of how interdisciplinary understanding and a change in participants' mental models cognitively arise.

Concerning its purpose, our workshop deviated from the more typical focus on a client's problem. Instead, we concentrated primarily on the development of an interdisciplinary systems perspective within and the better management of a research project. We used the system dynamics process to develop a boundary object (Black, 2013) that interconnects the different aspects of the COMPLEX project. The fact that the CLD had been put together in a participatory way by an interdisciplinary group also gave the project manager confidence that the CLD was reasonably comprehensive and that there were no substantial aspects of the research problem that were being neglected. The workshop also acted as an effective way of bringing many of the project's stakeholders together for the first time, at an early stage of the project. This provided an opportunity for them to get to know one another socially and to become more familiar with different disciplinary perspectives. However, the CLD's nature did present some limitations. The level of detail created during the workshop was too fine-grained to be useful as a project management tool but not detailed enough to be used to plan the project's modelling approach. Following the workshop, a simplified version was created for project management and to plan and allocate tasks, while the mathematical modelling that forms a substantial part of the research project has required processes such as mass transport to be defined in more detail than in the CLD and using well-defined equations. Another example of work that supports the use of participatory system dynamics for enhancing interdisciplinarity comes from a water-focused project (Zimmermann and Pluchinotta, 2020). Participatory system dynamics modelling to enhance the inter- and transdisciplinary management of projects thus seems to be a fruitful direction for further research.

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Facilitation activities and value to practice

It is useful to understand communication at the workshop not only through the lens of interdisciplinarity but also through that of facilitation. Our article shares this focus on the effects of facilitation with the study by McCardle-Keurentjes and Rouwette (2018). We analysed *what activities the facilitator uses to manage the workshop* (objective 2). The facilitator (but at times also participants) engaged in mainly five often co-occurring facilitation activities of asking, refining and suggesting, explaining, reproducing, and directing the discussion (see Figure 8). We found a big overlap of the facilitator asking questions, with refining and suggesting variables and causal links. Checking whether she understood participants correctly and suggesting in a very inquiring way how to represent their ideas in SD terms emerged as a way to ground the model in the participants' rather than the facilitator's experience.

We also analysed *how facilitation affects the workshop conversation* (objective 3). Understanding facilitation effects offers practical value, e.g. in helping participants taking up useful language. Through the activities of reproducing as well as refining and suggesting in particular, the facilitator exemplified 'model talk." The active use of these activities may help ease the link between storytelling and modelling. This seems particularly important at the beginning of variable elicitation as well as causal loop diagramming sessions to quickly familiarise participants with modelling conventions (see also Zimmermann, 2022). Knowing how to intervene meaningfully can give participants confidence and support an equal and truly interdisciplinary contribution to modelling. The frequently co-occurring asking for confirmation activity would ideally be added to check for agreement.

In the workshop, several participants brought in high levels of detail and the facilitator steered the discussion to a more abstract level, where interactions between different disciplines can be understood, and which is more typical for system dynamics modelling. In disciplinary topic transitions, it was the facilitator who most frequently drew the conversation to a middle-ground focus relevant to both museum practice and chemical science (see Figure 10). One could therefore conclude that facilitation can have an integrative effect. Different contexts may require very different interpretations of what such a middle-ground focus may mean. Yet, with some investigation into the context, it could actively be used by facilitators to make a conversation relevant to all participants.

Interestingly, we found that it is not only the facilitator who initiates topic transitions between a museum and chemical science focus, but that participants do this very frequently as well and occasionally even very consciously and in a facilitative mode (see Figure 9). Participants' facilitation then greatly affects the workshop conversation as well. For example, a scientific thinker in heritage supported the topic swing 3 from mass transfer to storage

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and the project lead's comment that "*There's definitely some important chemical processes missing*" moved the discussion to hydrolysis and chain scission in topic swing 5. Ensuring participants have a clear understanding of the model's and workshop's purpose can enhance facilitated modelling practice by active utilisation of participants' facilitation abilities. Then they can bring in their interdisciplinary perspectives and help build a whole-system view around the purpose and so assist in achieving the desired outcomes.

The workshop microanalysis allowed us to understand conversation dynamics over time, which revealed much interconnectedness and an accumulative nature of topic swings and instances of directing the discussion. Frequently, such large transitions were a team effort, with participants suggesting a new topic direction based on a facilitator's question or the facilitator taking up a novel thought that had lingered in the conversation. Consequently, rather than understanding facilitators as navigators who steer the conversation, we can regard them as catalysts and enablers who create shared meaning with participants in a recursive and cumulative way.

Using the framework for workshop microanalysis

Our study not only shares a focus on facilitation with that by McCardle-Keurentjes and Rouwette (2018), it also shares a focus with the *process* category of the coding framework used by Tavella and Papadopoulos (2015a, 2015b), which builds on earlier work by Huxham and Cropper (1994). Further similarities exist to codes in the *content* production and *process* categories by Cunico *et al.* (2023). In addition, we share a focus on cause-effect relationships and on a model with others (see Cunico *et al.*, 2023; Dwyer and Stave, 2008; Hager *et al.*, 2015; Kopainsky *et al.*, 2017; Stave *et al.*, 2019). It is useful to identify how our analysis categories compare to those used by other researchers. It helps understand the gap that our disciplinary/topic focus filled, allowing for a novel analysis of the dynamics of interdisciplinarity. The framework shows that our study has combined three different lenses, one each from the content, contribution, and facilitation category (see Table 2), which has been useful. As different lenses provide different insights, this complements previous studies, and we suggest further systematising different foci.

The framework can be used to look at participatory system dynamics work in great detail from different lenses, when multiple foci are combined. Going forward, we suggest using the framework to relate the different foci to different workshop scripts and activities, to use them in the analysis of a series of workshops of the same kind, e.g. with different groups, as well as to compare GMB workshops in the tradition of system dynamics with other facilitated or modelling workshops. In line with Franco and Rouwette (2011), we argue that the framework in Table 2 is not exhaustive but a preliminary list of lenses that can be enlarged by empirical and inductive work as well as theoretical categories.

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Limitations and future research

This study has limitations, for example, concerning the available data. We used audio recordings and transcripts of the workshop communication. They did not allow for an analysis of actions such as gestures (Franco and Nielsen, 2018) or an analysis of the construction process of the model itself and its link to the dynamics of the conversation (see Figure 5). For a micro-level study of a workshop, video material would have been desirable to link the spoken word to what the facilitator and participants do, how the model structure is drawn and amended, and how it influences the discussion. In addition to the video recording of live workshops, the increased practice of conducting participatory system dynamics workshops online (Wilkerson *et al.*, 2020; Zimmermann *et al.*, 2021) could allow easy access to such video-recorded material. As a resulting document for analysis, a video itself or a written transcript that includes notes on actions is thus recommended.

It may also be considered a limitation that, while certain analyses were conducted and compared by two coders, others were conducted by one coder, with a second person acting only as a critical friend and sense check to the results. The necessity to have a second coder is debated, with some requiring it for reliability and others considering intercoder reliability epistemologically problematic (Clarke and Braun, 2013). Consequently, different readers may have varying opinions on the significance of this limitation. We perceive the reflective process stimulated by intercoder discussion as its greatest benefit, which we clearly lack for facilitation-related coding and could only attempt to mimic by multiple rounds of coding. Overall, we believe that the individual perspective each coder brings is both a benefit and a limitation. While a coder's perspective limits the view, it also broadens it in some areas to specific elements that others would find more difficult to see.

While also being a clear benefit, the study's heritage science context may be considered as a limitation as well. The disciplinary distinction of a museum practice, science, or both focused discussion provided interesting insights on dynamic transitions between these, but such trifold distinction may not be prevalent in other contexts. Thus, further analyses of either fewer or more thematic foci, also in the absence of foci that bridge between the single-disciplinary foci, may be required.

A further limitation includes the fact that, although our analysis portrays multiple dynamics during a workshop, it still only provides a snapshot of the entire project within which the workshop is embedded. We gathered evidence on the participants' longer-term workshop impression and use through interviews, but future research could provide an even deeper, e.g. repeated analysis on how workshop microprocesses affect workshop outcomes in terms of participant cognition, interdisciplinarity, and project management over time.

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Concerning participant cognition, the participant contributions revealed their different disciplinary mental models. For example, museum practitioners more likely talked about museum objects, whereas those with a scientific background more likely talked about material properties and molecular phenomena, i.e. chemistry. Given the increased speed of big swings between a museum practice and chemical science focus in the communication, future research may go further into depth on thinking at different scales, e.g. a molecular, material, or object scale in this case, and on the accelerating topic shifts.

Our present analyses suggest multiple further avenues for future research. Many suggestions relate to the microlevel analyses of facilitation. As the facilitator initiated a particularly large part of the transitions to a focus on both topics, future research can investigate whether this is a consistent phenomenon across workshops and across facilitators. It would be interesting to investigate to what extent the co-occurrence of suggesting how to represent a participant statement in model structure and at the same time asking participants their opinion about this representation is a consistent phenomenon across SD workshops. This can be related to the resulting model, e.g. a model conforming more to SD practice versus a model very true to the participants' initial wording. As we noted that some nonfacilitators occasionally engaged in a facilitative way as well, it would be interesting to further investigate when this occurs, whether it depends on the person's role (e.g. gatekeeper, project lead), expertise, seniority, or other factors.

With its focus on chemical processes in museum artefacts, our workshop had an uncommon content focus, plus an innovative purpose, intended to support the management of an interdisciplinary research project. Concerning content, the application of SD modelling to chemical processes is unusual (e.g. D'Anna *et al.*, 2008). Related applications usually model the concentration of substances with or without behavioural effects. System dynamics seems promising for supporting an innovative systems view within the chemistry discipline, where many processes are still analysed in isolation and insights into their interactions are lacking (Curran, 2018).

As indicated above already, recommendations for future research also include meaning making in participatory SD and the use of SD boundary objects for project management as well as the application of the framework for workshop microanalysis to diverse types and series of workshops.

Conclusion

In summary, our study into the microprocesses of conversation dynamics in a group model-building workshop found that interdisciplinarity manifests

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itself in different ways, with frequent interdisciplinary transitions interacting with large interdisciplinary swings in the topic of discussion. The facilitator supported this by activities such as direct asking, referring to what participants had said and building on it, and by directing the discussion or explaining process. Facilitation activities support the conversation by exemplifying language that allows participants to relate their experience to a developing model, by contributing to the recursive development of shared meaning and by helping make the conversation relevant to all present.

We hope our analysis and framework will be valuable for a greater emphasis on the microprocesses and dynamics of SD workshops, i.e. the detail of what happens when doing participatory SD. The focus on dynamics and on interdisciplinarity can be useful starting points for such work. The collaboration for this study was an enjoyable endeavour into interdisciplinarity itself, and the authors believe that our diverse disciplinary backgrounds allowed us to take a novel approach to the analysis, linking molecular, material, and object scales and chemical-science and museum-practice topics with system dynamics processes and facilitation.

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Supporting information

Additional supporting information may be found in the online version of this article at the publisher's website.

Data S1: Script/workshop runsheet, interview guide, coding framework and CLD.

Video S1: Animation of the dynamics of the conversation, indicating the topic of discussion and speaker category (refined from Curran and Zimmermann, 2022).

Data S3: Resulting CLD from the workshop in Vensim software.

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