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Life cycle assessment of in-person, virtual, and hybrid academic conferences

New evidence and perspectives

Antonio Cavallin Toscani[1,2] | Atalay Atasu[2] | Luk N. Van Wassenhove[2] | Andrea Vinelli[1]

[1]Department of Management and Engineering, University of Padova, Padova, Italy

[2]Technology and Operations Management Area, INSEAD, Fontainebleau, France

Correspondence
Antonio Cavallin Toscani, Stradella San Nicola, 3, 36100, Vicenza, Italy.
Email: antonio.cavallintoscani@unipd.it

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Abstract

This study contributes to the debate on the environmental impacts of academic conferences by comparing the life cycle impacts of a sample of real-world in-person, virtual, and hybrid conferences with different features and organizers. Results show that virtual formats reduce impacts by two to three orders of magnitude across all impact categories (for global warming, averagely from 941.9 to 1.0 kg CO_{2eq} per person). The hybrid case study, with a share of 69% virtual attendees, displays an average 60% reduction in indicator results, less than ideal cases where the farthest attendees join online. The cross-conference comparison allowed identifying several drivers of impact variation. For in-person conferences, some never addressed drivers were uncovered, including the energy sources and systems used to supply the venue or the number of non-local staff members and exhibitors. For virtual conferences, the main impact driver is the average time spent online by delegates, surprisingly more related to virtual experience design (e.g., synchronous vs. asynchronous presentations) than conference duration. The study further summarizes mitigation options from the literature and proposes new ones, such as selecting a venue supplied by a biomass-fueled district heating system or with a green electricity contract (around −41 and −1.9 kg CO_{2eq} per person, respectively). Lastly, our work highlights some inconsistencies that affect current conference assessments and proposes new research avenues, advocating the need to shift the focus from optimizing single conferences to considering the optimal portfolio of conferences and other activities for academic societies to meet their members' needs while minimizing environmental impacts.

KEYWORDS
academic conferences, environmental impacts, hybrid events, industrial ecology, life cycle assessment, virtual events

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1 INTRODUCTION

Conferences represent a well-established practice in academia to facilitate the creation and dissemination of knowledge (Rowe, 2018). They serve multiple important roles in the career of academics, enabling them—among others—to promote their work, attract feedback, and meet like-minded peers to build new research collaborations (Donlon, 2021). These benefits, however, come with a significant drawback: conferences can be a high resource-demanding and emission-intensive process (Hischier & Hilty, 2002). In the past two decades, scholars in different fields have started to disclose the greenhouse gas (GHG) emissions associated with conferences, especially conference travel, showing alarming figures (Jäckle, 2019; Kuper, 2019). For instance, Klöwer et al. (2020) found that the per-capita footprint of scientists traveling to the 2019 Fall Meeting of the American Geophysical Union was about 3 tons of CO_{2eq}, greater than the amount many citizens around the world emit over an entire year.

Against this backdrop, a growing movement has started to question the established model of in-person conferencing and advocate the need, well before the Covid-19 pandemic, to leverage the significant improvements in videoconferencing technologies to switch to more sustainable formats, such as virtual or hybrid conferences (Fraser et al., 2017; Reay, 2003). A few pioneers led the way—see Dolci et al. (2011)—but these were isolated cases. The pandemic, however, upended the conference landscape and forced the switch to virtual formats to happen suddenly across all fields. Many regarded it as a great opportunity for academia to reinvent its conferencing model (Jordan & Palmer, 2020). More recently, some conferences have also experimented with hybrid formats, where some attendees join in person and others virtually (Langin, 2021). With the world progressively reopening, organizers are confronted with the task of designing the conferences of the future and are looking for evidence to make informed decisions.

From an environmental perspective, however, Tao et al. (2021, p. 2) highlight that "there is a minimal quantitative understanding of the environmental impacts from different modes of conferences. To understand the sustainability implications of future conferences and inform the policies, it is essential to quantify the environmental footprints of virtual, in-person, and hybrid conferences."

Previous studies have extensively analyzed the GHG emissions associated with travel to in-person conferences and ways to reduce them (Burtscher et al., 2020; Coroama et al., 2012; Desiere, 2016; Fois et al., 2016; Jäckle, 2019; Klöwer et al., 2020; Kuonen, 2015; Kuper, 2019; Orsi, 2012; Ponette-González & Byrnes, 2011; Spinellis & Louridas, 2013; Stroud & Feeley, 2015; van Ewijk & Hoekman, 2021). Among these, a few studies also considered virtual and hybrid conferences, either treating them as carbon-neutral scenarios (Jäckle, 2019; van Ewijk & Hoekman, 2021) or assessing their footprint in a simplified way (Burtscher et al., 2020; Klöwer et al., 2020). Some studies adopted a broader scope and conducted comprehensive life cycle assessments (LCA) of in-person conferences' impacts (Astudillo & AzariJafari, 2018; Hischier & Hilty, 2002; Neugebauer et al., 2020), considering activities other than delegate travel, such as accommodation, and impact categories other than climate change, such as human toxicity, thus providing richer insights to organizers. Among these, Hischier and Hilty (2002) also considered the virtual format, even if modeled through a conjectural scenario, whereas none assessed comprehensively the impacts of a hybrid conference. Two recent articles addressed this gap, both leveraging the data from a virtual conference of the Covid era and building in-person and hybrid counterfactuals through scenario analysis (Jäckle, 2021; Tao et al., 2021). Table S1.1 in Supporting Information S1 provides a summary of previous studies regarding their scope and main methodological choices.

Notably, none of the comprehensive LCA studies considered multiple conferences with different features (e.g., size, location, and audience), thus hampering the transferability of the results and making it difficult to highlight potential drivers of impact variation across different conferences. Some non-LCA travel-focused studies considered multiple events (Jäckle, 2019; van Ewijk & Hoekman, 2021)—typically of the same academic society—but their limited scope prevented the identification of drivers of impact variations within processes other than travel and trade-offs between different impact categories. Regarding format comparison, then, the exclusive reliance on scenario analyses means that the actual choices of stakeholders in real-world settings remain unknown and the projected results need validation. Lastly, while some studies have identified a few issues affecting the validity of format comparisons, such as functional equivalence (Hischier & Hilty, 2002) and ripple/rebound effects (Coroama et al., 2012; Takahashi et al., 2006), to the best of our knowledge, none has comprehensively and critically investigated the inconsistencies related to current conference assessments/comparisons, which may have led to an overemphasis of some issues and the neglection of others.

To address these gaps and move the debate forward, the goals of this study are to (1) quantify and compare the overall environmental impacts of real-world in-person, virtual, and hybrid conferences; (2) identify potential drivers of impact variation across conferences with a different size, location, duration, organizer, and audience; and (3) investigate the inconsistencies that can affect the validity of conference assessment results. Additionally, a summary of the main mitigation options proposed in the previous literature and an investigation of some never-considered ones are also included in the scope of the study. To this end, we leverage comprehensive LCA data gathered from a sample of conferences organized by three academic societies in the field of Operations Management and Operations Research (OM&OR): the US-based *Institute for Operations Research and the Management Sciences* (INFORMS), *Production and Operations Management Society* (POMS), and the Europe-based *European Operations Management Association* (EurOMA).

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TABLE 1 Conferences under study.

Conference	Format	Period	Duration[a]	Attendees	Venue
INFORMS 2019	In-person	October 2019	4 + 1 days	7072	Seattle (US): Washington State Convention Center + Sheraton Grand Seattle
INFORMS 2020	Virtual	November 2020	6 + 1 days	5501	Online: in-house virtual platform + Zoom
INFORMS 2021	Hybrid	October 2021	4 + 1 days	6109 (1921 in-person)	Anaheim (US): Anaheim Convention Center + Anaheim Marriott. Online: in-house virtual platform + Zoom
POMS 2019	In-person	May 2019	4 + 1 days	2000	Washington DC (US): Washington Hilton
POMS 2021	Virtual	April–May 2021	5 + 1 days	1488	Online: in-house virtual platform + Zoom
EurOMA 2019	In-person	June 2019	3 + 2 days	561	Helsinki (FI): Hanken School of Economics + Aalto University Business School
EurOMA 2021	Virtual	July 2021	3 + 1 days	340	Online: Exordo virtual platform

[a]Additional days include pre-conference events such as doctoral seminars, business meetings of academic journals/societies, special interest groups, and so on.

2 | METHODS

The LCA method in compliance with ISO 14044 standard was implemented, including its four phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation of the results (ISO, 2017).

2.1 | Goal and scope definition

To achieve the goals stated above, we selected a convenience sample of conferences held in different formats (in-person, virtual, and hybrid) and with different features (organizer/audience, size, location, duration, period). Particularly, given the high data and resource requirements of LCA, we targeted the most recent annual meetings organized in each available format by the supporting societies, which guaranteed both the availability of accurate data and the desired heterogeneity (Table 1).

2.1.1 | Functional unit

According to LCA standards, "*comparisons between systems shall be made on the basis of the same function(s), quantified by the same functional unit(s)*" (ISO, 2017, p. 8). When considering different conference formats, though, it has long been evident that videoconferencing solutions do not perform the same functions as in-person meetings (Takahashi et al., 2006). A survey we ran with the members of supporting societies—object of another article we are writing—found that virtual conferences are not able to provide the same networking and socialization opportunities as in-person, even if they provide other functions, such as greater flexibility and accessibility for underrepresented groups. That perfectly aligns with the discussion provided by Hischier and Hilty (2002) and Coroama et al. (2012), who claim that it is difficult to assume functional equivalence when alternatives involving the use of electronic versus conventional media are compared (e.g., telecommunication as a substitute for in-person interaction). New media will always bring advantages and disadvantages with them—that is, different functions—which makes the LCA requirement of functional equivalence less and less adequate in the area of information technology. In Section 3.4, we propose some solutions to tackle functional (in)equivalence in conference format comparisons. For the purpose of the analysis hereby presented, we followed the same pragmatic approach as Tao et al. (2021) and defined the functional unit (FU) as "*one average conference participant*," which, despite not addressing functional equivalence concerns, provides a sound basis for a fair comparison across different conferences and formats.

As an alternative to our FU, Hischier and Hilty (2002) and Neugebauer et al. (2020) refer to "*holding a 3-days conference*" in their single case studies, but such an FU would not be suitable for comparing multiple conferences with different sizes and durations. A per participant-day FU may instead sound reasonable having conferences with different durations, but we did not adopt it for two reasons: (i) all in-person conferences in our sample had the same duration when considering pre-conference events, which is quite standard in the OM&OR field; (ii) for virtual conferences, as we show in Section 3, duration is not clearly related to how much people attend the event, which makes it a not relevant functional characteristic—based on our experience, this is the case for in-person conferences too, as attendance is largely constrained by other professional/private commitments.

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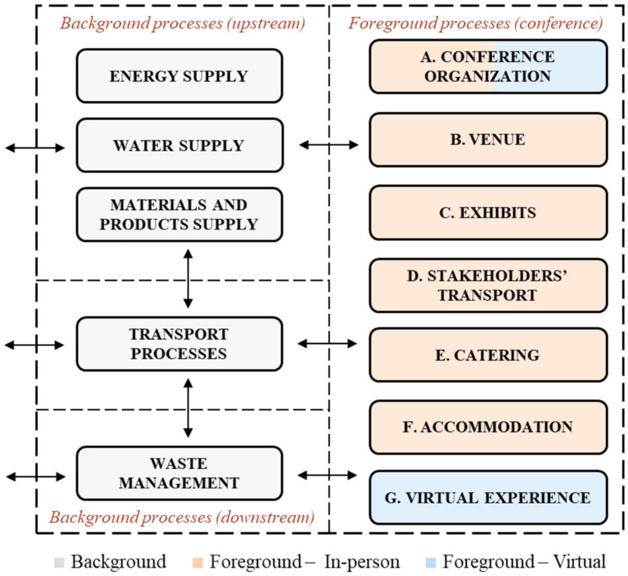

FIGURE 1 Life cycle assessment model for academic conferences.

2.1.2 | System boundary

To define the system boundary, we mostly referred to Neugebauer et al. (2020) and Tao et al. (2021), the only studies that considered the overall life cycle impacts of academic conferences. We further integrated input from Cavallin Toscani et al. (2022), who provided a comprehensive life cycle representation for any type of event. Figure 1 shows the resulting LCA model. On the left side, there are the background processes that provide energy, material, and product inputs to conference activities or dispose of their waste outputs. To model them, we relied extensively on internationally recognized LCI databases (see Section 2.1.3). On the right are the foreground processes that cluster the impactful activities associated with conference organization and delivery. To model them, we mostly relied on primary data provided by conference organizers or secondary data retrieved from literature (see Section 2.2).

Regarding the foreground processes that characterize in-person conferences, *Conference organization* refers to general planning activities, such as conference-related board meetings, venue inspection visits, organizing committee's and secretariat's activities, track and session chairs' activities, pre-conference participants' activities, and conference materials—including their production, shipping, and disposal. *Venue* refers to the conference-related use of the venue and buildings, mostly including the energy consumption of conference rooms and equipment. *Exhibits* include the production, transportation, and disposal of exhibition and/or career fair materials, where applicable.[1] *Stakeholders' transport* refers to the transportation of attendees, exhibitors, and staff to reach the conference site, and, where applicable, for industry visits. *Catering* includes the production and transportation of food and beverage items consumed at the conference. Lastly, *Accommodation* refers to overnight stays of conference stakeholders.

For virtual conferences, *Conference organization* has the same meaning as before, even though in this context most activities are virtualized and dematerialized. *Virtual experience* refers to the use of electronic and internet devices to connect event participants during and after the event, including the direct energy use and the indirect energy and materials used for device production. Hybrid conferences are, environmentally speaking, simply a concatenation of previous formats. Additional equipment is required to live stream presentations from the venue (Coroama et al., 2012), but in our model, this extra consumption is absorbed by the *Venue* process.

Table S1.1 shows how our boundary compares to that adopted in previous studies. As an extension, we considered some never assessed impacts, such as those associated with venue inspection visits, participants' registration activities, the life cycle of exhibition materials, the transportation and accommodation of conference stakeholders other than delegates (i.e., sponsors, exhibitors, and staff), and, for virtual conferences, platform visits and downloads after the conference. As we show in Section 3, some of these items represent significant impact drivers. Conversely, we did not consider some activities/flows, excluded mostly due to the lack of accurate primary/secondary data and/or a lack of relevance to the overall results. These encompass: (a) computer usage for abstract and/or full paper drafting, (b) composite gadgets distributed to attendees (e.g., safety kits), (c) venue water and other material consumption (e.g., cleaning products), (d) travel of stakeholders in their country to reach the airport/station of departure and (e) within the conference location for extra-event activities, (f) energy and water use for food preparation, (g) extra-conference consumption of food and other commodities, and, for virtual conferences, (h) home consumption of food, energy, and water during the conference. Some of these items—(a), (d), (f), (h), and partly (c) and (g)—were modeled by Neugebauer et al. (2020) and/or Tao et al. (2021) through approximate secondary data and, in general, showed a negligible or very low contribution to the overall results, which justifies our exclusion. An exception is

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item (h), which Tao et al. (2021) showed to make up most of the virtual conferences' impacts. Its exclusion from our assessment depends on another criterion we adopted, that is, the unclear allocation of impact responsibility to the conference—valid also for items (e) and (g). Differently from Tao et al. (2021), indeed, we opted here for a "*control*" approach (Cavallin Toscani et al., 2022), where only activities under the control of conference organizers are considered, as further discussed in Section 3.4.

2.1.3 | LCI databases and LCIA methods

The *SimaPro* software and LCI databases therein implemented were employed to perform the analyses. Particularly, we made extensive use of the *ecoinvent 3.8* database (Wernet et al., 2016) as our primary source of LCI data for background processes. When available, datasets with geographical coverage related to the country/region where the conference took place were selected, otherwise, globally averaged datasets were used. In rare cases in which the needed process datasets were not available—especially for food production—we further relied on *Agri-footprint 5.0* (Paassen et al., 2019) database. The list of employed datasets for each analyzed conference is available in Supporting Information S2-S8.

For the LCIA, in line with our goal to run a comprehensive assessment and comparison, we followed Tao et al. (2021) and selected the ReCiPe method, at the midpoint level with the hierarchist perspective, one of the most established and comprehensive methods worldwide (Huijbregts et al., 2017). It incorporates a large set of impact categories, namely Global warming (GW), Stratospheric ozone depletion (SOD), Ionizing radiation (IO), Ozone formation-Human health (OF-HH), Fine particulate matter formation (FPMF), Ozone formation-Terrestrial ecosystems (OF-TE), Terrestrial acidification (TA), Freshwater eutrophication (FEu), Marine eutrophication (MEu), Terrestrial ecotoxicity (TEc), Freshwater ecotoxicity (FEc), Marine ecotoxicity (MEc), Human carcinogenic toxicity (HCT), Human non-carcinogenic toxicity (HnCT), Land use (LU), Mineral resource scarcity (MRS), Fossil resource scarcity (FRS), and Water consumption (WC). Unlike Tao et al. (2021), we implemented the updated version of the method—from 2016—which provides characterization factors representative of the global scale instead of the European scale (Huijbregts et al., 2017).

2.2 | Life cycle inventory

For each conference, primary and secondary data were collected for all foreground processes in Figure 1. Sources of primary data were the conference organizers and/or society leaders, who gave us access to conference-related documents and answered our questions in ad hoc interviews. Examples of primary data include transportation information for venue inspection visits by organizing staff, quantities of purchased conference materials, the actual amount of time delegates were connected during virtual conferences, and so on. Despite this data availability, many assumptions and secondary data had to be used to make provided information usable in an LCA setting or fill data gaps. We strived to remain consistent and when there were gaps for a conference, missing data were either extrapolated from other conferences in the sample or derived from other LCA studies or online resources (e.g., e-commerce websites for the material composition of purchased products, when not specified). As prescribed by ISO 14044, all assumptions, data sources, and collection/calculation procedures were documented in ad hoc data collection sheets to increase transparency and replicability. Particularly, for all conferences, we created a spreadsheet that details the list of modeled activities and related sub-activities/materials, and, for all sub-activities, it specifies: the name of the linked ecoinvent dataset containing relevant background data, the measured/calculated value of the flow,[2] the unit of measure, and all relevant information and assumptions regarding data collection/calculation—including the indication of secondary data sources, if used. These spreadsheets are available in Supporting Information S2-S8, to which we refer for inquiries regarding specific flows or activities. In Supporting Information S1.2, instead, the general logic and main assumptions we used to calculate the inventory of each unit process are described.

3 | RESULTS AND DISCUSSION

3.1 | Life cycle impact assessment results

Regarding the impact quantification and comparison across formats, Table 2 reports the LCIA results for the analyzed conferences. The first row related to the GW category shows the per-capita carbon footprints, with an average of 941.9 kg CO_{2eq} for in-person conferences and 1.0 kg for virtual—almost three orders of magnitude of difference. The last instead related to the WC category displays the water footprints, with an average of 2602.7 L for in-person and 9.0 L for virtual—more than two orders of difference. For other impact categories as well, the difference between in-person and virtual is mainly between two and three orders of magnitude. To understand the scale of such difference, the carbon footprint of an average in-person attendee alone is about twice the total footprint of EurOMA 2021 (488.3 kg CO_{2eq}).

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TABLE 2 LCIA results.

Impact category	Unit	In-person INFORMS 2019	POMS 2019	EurOMA 2019	Virtual INFORMS 2020	POMS 2021	EurOMA 2021	Hybrid INFORMS 2021	Only in-person[a]
GW	kg CO_{2eq}	9.87E+02	1.07E+03	7.65E+02	7.15E-01	9.87E-01	1.44E+00	4.01E+02	1.28E+03
SOD	kg $CFC11_{eq}$	2.78E-04	3.20E-04	2.52E-04	3.17E-07	4.26E-07	6.15E-07	1.16E-04	3.70E-04
IR	kBq Co-60_{eq}	1.20E+01	1.37E+01	1.13E+01	6.91E-02	1.13E-01	1.67E-01	4.74E+00	1.51E+01
OF-HH	kg $NO_{x\ eq}$	4.72E+00	4.95E+00	3.45E+00	1.98E-03	2.31E-03	3.34E-03	1.84E+00	5.85E+00
FPMF	kg $PM2.5_{eq}$	1.02E+00	1.08E+00	7.72E-01	1.53E-03	2.22E-03	3.22E-03	4.01E-01	1.27E+00
OF-TE	kg $NO_{x\ eq}$	4.76E+00	5.00E+00	3.48E+00	2.01E-03	2.34E-03	3.38E-03	1.86E+00	5.91E+00
TA	kg $SO_{2\ eq}$	2.94E+00	3.11E+00	2.24E+00	2.85E-03	3.75E-03	5.40E-03	1.16E+00	3.69E+00
FEu	kg P_{eq}	2.04E-01	2.17E-01	1.71E-01	4.37E-04	6.53E-04	9.23E-04	7.88E-02	2.51E-01
MEu	kg N_{eq}	2.24E-02	2.58E-02	2.61E-02	5.07E-05	8.03E-05	1.09E-04	8.53E-03	2.71E-02
TEc	kg 1,4-DCB_{eq}	1.83E+03	1.97E+03	1.41E+03	4.63E+00	4.33E+00	5.87E+00	7.49E+02	2.38E+03
FEc	kg 1,4-DCB_{eq}	7.90E+00	9.94E+00	7.41E+00	1.20E-01	1.62E-01	2.18E-01	3.75E+00	1.19E+01
MEc	kg 1,4-DCB_{eq}	1.14E+01	1.41E+01	1.05E+01	1.55E-01	2.10E-01	2.83E-01	5.33E+00	1.69E+01
HCT	kg 1,4-DCB_{eq}	9.19E+00	1.17E+01	7.89E+00	3.96E-02	6.00E-02	8.47E-02	4.34E+00	1.38E+01
HnCT	kg 1,4-DCB_{eq}	3.28E+02	3.77E+02	2.51E+02	1.86E+00	2.48E+00	3.34E+00	1.41E+02	4.48E+02
LU	m^2yr $crop_{eq}$	2.19E+01	2.82E+01	3.94E+01	1.61E-02	2.10E-02	2.99E-02	9.34E+00	2.97E+01
MRS	kg Cu_{eq}	5.24E-01	6.76E-01	4.62E-01	6.20E-03	7.99E-03	1.05E-02	2.56E-01	8.15E-01
FRS	kg oil_{eq}	3.14E+02	3.43E+02	2.42E+02	1.88E-01	2.47E-01	3.60E-01	1.28E+02	4.08E+02
WC	m^3	2.46E+00	2.73E+00	2.63E+00	5.64E-03	8.84E-03	1.27E-02	9.34E-01	2.97E+00

[a]Indicator results for INFORMS 2021 in-person attendees only.

Figures 2 and 3 display for each in-person and virtual conference, respectively, the contributions of all conference stages to the single impact categories, normalized against the indicator results of the conference with maximum impact. For in-person conferences, in line with Neugebauer et al. (2020), *Stakeholders' transport* dominates most impact categories, with particularly large shares in those driven by fossil fuel consumption, such as GW (~93% averagely), OF-HH/TE (~97.6%), and FRS (~93%). *Accommodation* instead is the primary contributor to MEu (~63.9%) and WC (~56.8%), with significant shares also for FEc and MEc, driven by the material and energy consumption of hotel operations. The *Venue* process has an average share of 2.5% across all categories and conferences, with a maximum of 9.5% for IR, due to the consumption of electricity produced from nuclear power in some conference locations (e.g., Finland for EurOMA 2019). Food production for *Catering* is responsible for a large share in the LU category (37%), and the shares of 18.8% and 12.1% in the WC and MEu categories. The latter two are also significantly driven by *Conference organization*, with contributions of 8.1% and 9%, respectively, mostly due to the production of conference materials. Lastly, *Exhibits* have a neglectable impact across all categories (average of 0.05%).

Virtual conferences, instead, have a more stable pattern across categories, with *Virtual experience* responsible for greater impact shares than *Conference organization*—59.2% versus 40.8% on average—both driven by the energy consumption of electronic devices and the material consumption for their production.

Focusing on INFORMS 2021—the first hybrid conference ever assessed—the impact breakdown is reported for both in-person (Figure 2) and virtual (Figure 3) attendees. For the former, the impact profile looks equivalent to that of an in-person event. Impacts are larger than other conferences for reasons that are explained in the next section (e.g., greater traveled distances). For virtual attendees, instead, the impact profile looks quite different from other virtual conferences. That occurs because the *Conference organization* stage includes the planning activities for the whole event, including those for the in-person component that are more energy and material demanding. The *Virtual experience* stage is instead similar to INFORMS 2020. What is not captured in previous graphs is the overall benefit of a hybrid event (see Table 2). Compared to INFORMS 2019, an average 60% reduction is obtained in the overall per-capita indicator results. This is around 20% less than what was projected by Tao et al.' (2021) simulation with the same share of virtual attendees (68.6%). Indeed, they considered an ideal scenario in which the farthest attendees join online. In real cases, that can hardly be enforced by organizers without incurring discriminatory behavior. However, they might design ad hoc incentives and promotion campaigns to attract a larger share of virtual attendees and prompt faraway delegates to attend online.

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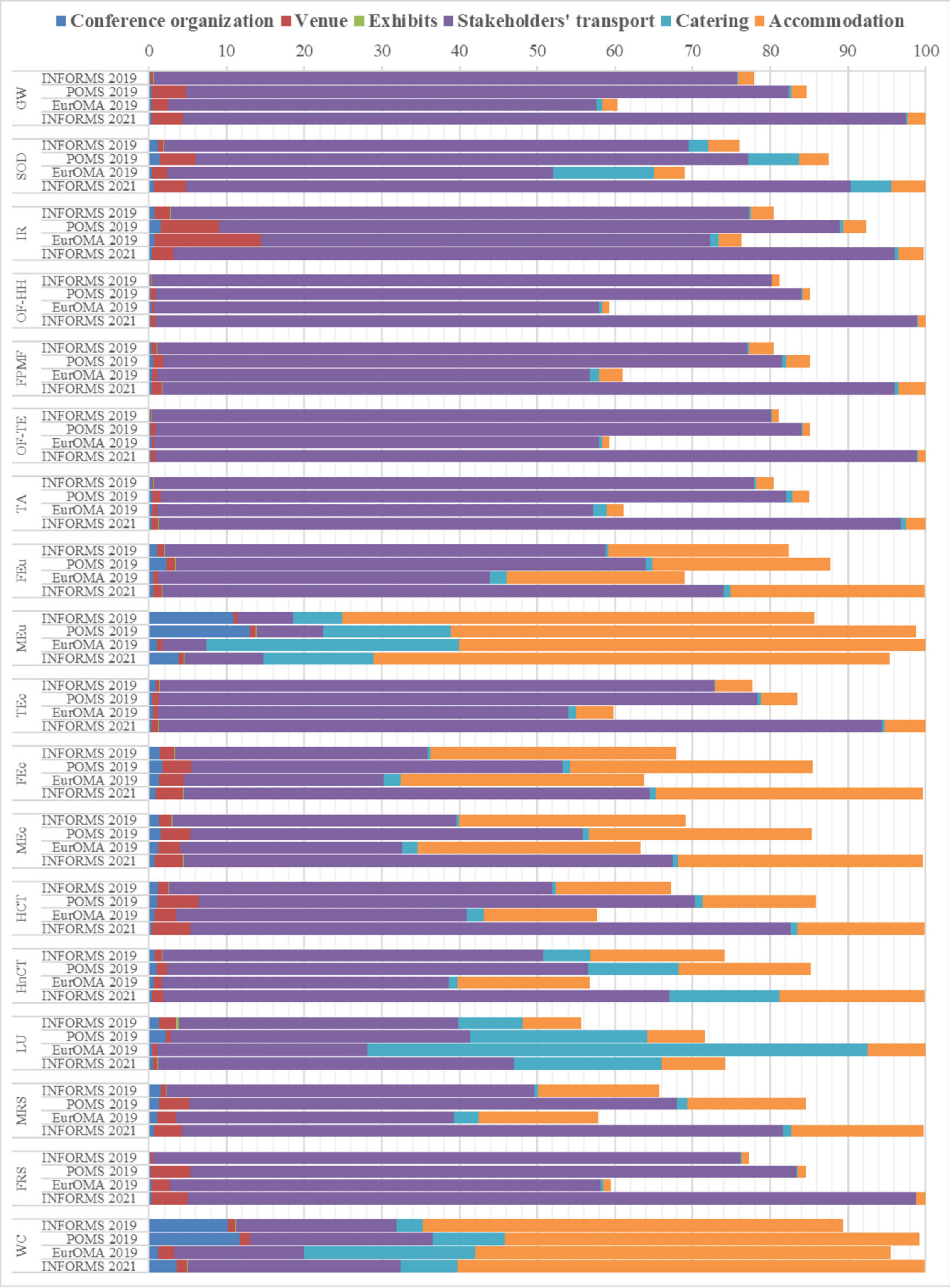

FIGURE 2 Impact breakdown by conference stage for in-person conferences. The underlying data for this figure can be found in Supporting Information S9.

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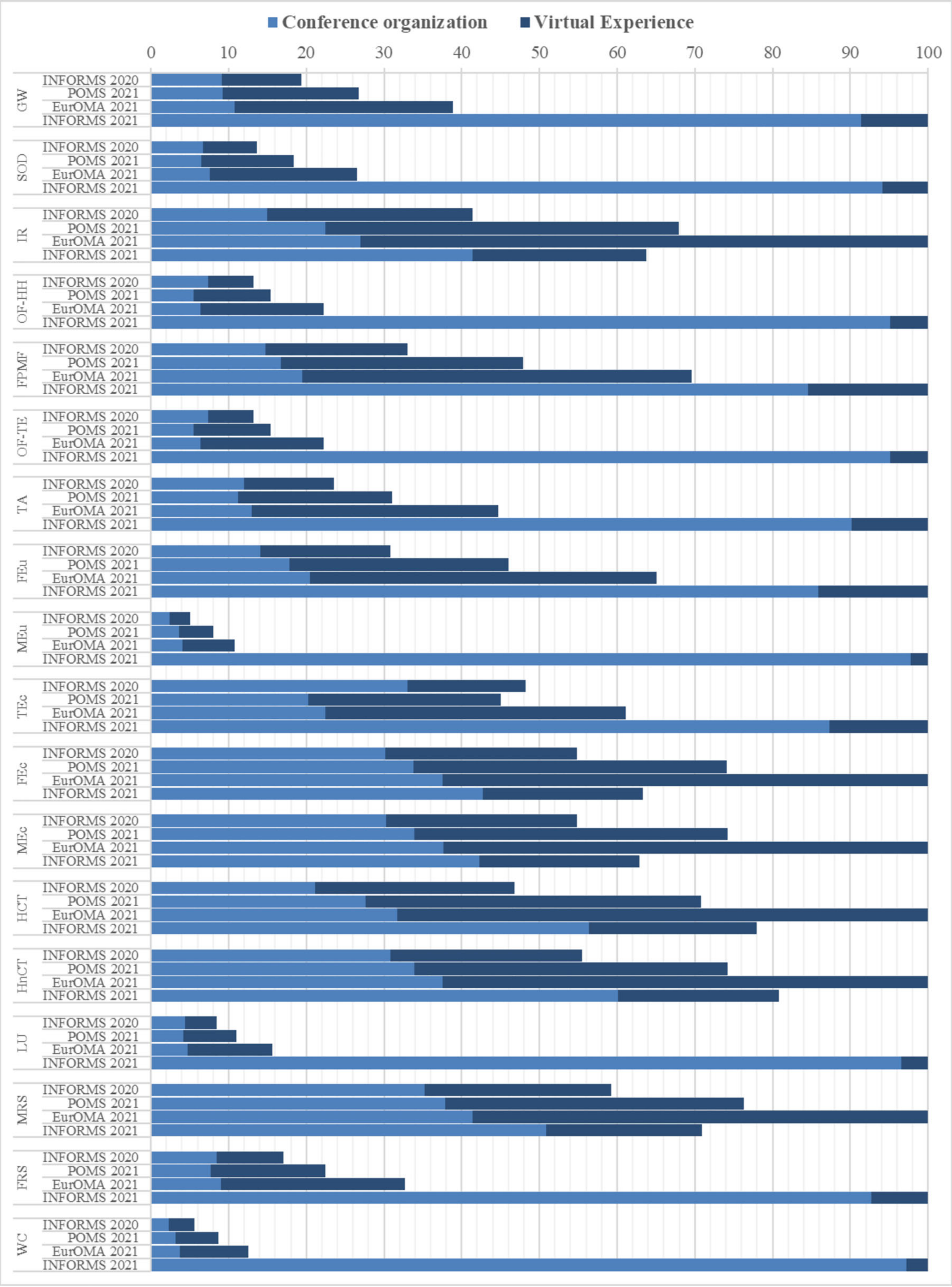

FIGURE 3 Impact breakdown by conference stage for virtual conferences. The underlying data for this figure can be found in Supporting Information S9.

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TABLE 3 Travel patterns by type of transport within in-person conferences.

	Conference	Type of transport					
		Landbound[a]	Air—Very short haul	Air—Short haul	Air—Medium haul	Air—Long haul	Total or average
Share of travelers (%)	INFORMS 2019	7.6	0.1	2.7	39.1	50.5	100
	INFORMS 2021	5.9	3.3	1.4	39.1	50.3	100
	POMS 2019	15.8	16.8	11.6	13.9	42.0	100
	EurOMA 2019	7.5	8.6	10.9	52.8	20.3	100
Average traveled distance (km)	INFORMS 2019	163.46	1403.50	2365.56	5860.49	13757.71	9324.64
	INFORMS 2021	167.18	1227.28	2293.03	5954.92	15534.27	10228.20
	POMS 2019	619.63	1322.32	2139.62	4842.56	19676.19	9502.63
	EurOMA 2019	40.00	897.44	2305.67	4547.03	20160.58	6826.43
Share of transport GHG emissions (%)	INFORMS 2019	1.3	0.0	0.8	24.6	73.2	100
	INFORMS 2021	3.5	0.6	0.4	22.3	73.3	100
	POMS 2019	3.8	3.6	3.1	6.9	82.6	100
	EurOMA 2019	1.2	1.8	4.4	35.0	57.7	100

[a] *Share of travelers* and *Average traveled distance* do not include the airport–venue connection for air travelers, while *Share of transport GHG emissions* does.

3.2 | Drivers of impact variation

Regarding potential drivers of impact variation, our identification strategy was primarily based on spotting significant differences across the impact profiles of conferences within the same format and working backward to find the reasons behind them.

For in-person conferences, a large variation can be seen in the impacts of *Stakeholders' transport*, with INFORMS and POMS attendees displaying greater travel impacts than EurOMA ones. As expected, this is mainly related to the average traveled distances, with POMS and INFORMS attendees traveling greater distances than EurOMA ones (see Table 3 for a summary of travel metrics). EurOMA has indeed a more concentrated audience with a prevalence of medium-haul travelers from Europe—typical of European conferences (Desiere, 2016). The American conferences, instead, have a larger share of long-haul travelers, mostly coast-to-coast travelers in the US and inter-continental travelers. POMS 2019, particularly, has a larger share of non-US attendees, which explains its greater average distance than INFORMS 2019. This does apply to INFORMS 2021, probably due to its location in Los Angeles which allowed for better flight connections.

The greater distances traveled by INFORMS 2021 attendees, however, seem not to explain alone their much larger transportation footprint. We discovered an extra impact associated with the transportation of staff and exhibitors. EurOMA and POMS represent typical small/middle-size societies with contained organizational structures. In their conferences, mostly local student volunteers are hired as staff and exhibitors encompass only a few publishers and companies. INFORMS is instead a more structured organization that combines local staff with full-time staff traveling from event to event. Its conferences further involve a large exhibition space with dedicated personnel from many companies and recruiting institutions. The allocation of staff and exhibitors' travel to attendees explains the impact surplus: +11.2% for the per-capita travel footprint of INFORMS 2021, +2.1% for INFORMS 2019, and +0.2/0.5% for POMS and EurOMA. The same applies to *Accommodation* impacts, which are greater for INFORMS conferences ceteris paribus. The effect is proportional to the ratio between the number of non-local workers and the number of attendees: around 1 every 100/200 at EurOMA and POMS, 1 every 50 at INFORMS 2019, and 1 every 10 at INFORMS 2021. Interestingly, the total number of staff members at INFORMS 2021 was greater than in 2019 (222 vs. 150), against a number of in-person attendees that was less than one third. This may be attributable to several reasons (e.g., greater complexity of running a hybrid event and unexpected reductions in the number of in-person attendees), which need further investigation.

Another significant difference regards *Venue* impacts, which are much lower across all categories for INFORMS 2019: for GW, 2.9 kg CO_{2eq} per person versus 56 kg of POMS 2019. This is due to the different energy sources and supply systems used to produce the heat consumed at the venue. For INFORMS 2019, indeed, a district heating system fueled by wood waste was used to supply conference buildings, less impactful than the traditional gas boilers employed in other venues. Other potential drivers for *Venue* impacts are the period and location in which the conference is held, which we did not capture because of the use of yearly and geographically averaged data. Spring and fall conferences are likely less energy demanding than winter and summer ones, depending on the location.

Another variation can be noticed in the impacts of *Catering*, which are larger across all categories for EurOMA 2019, a surprising result since its organizers purposefully offered a vegetarian-only menu for most meals. This can be explained by the consolidated practice in European conferences of covering most meals within registration fees, as opposed to most American conferences where only a few receptions and luncheons are offered—4 meals per registrant at EurOMA versus 1.5 at POMS and 0.5 at INFORMS. Integrating the food consumed outside the conference—often fast

TABLE 4 Main drivers of impact variation for academic conferences.

Format	Driver	Affected stages
In-person	Average distance traveled by attendees → Membership distribution vs. conference location	Stakeholders' transport
	Number and origins of staff, exhibitors, recruiters → Society size and value proposition	Venue, Exhibits, Stakeholders' transport, Accommodation
	Energy source and supply system → Conference location and venue	Venue
	Conference period vs. conference location	Venue
	Number and types of meals	Catering
	Number and types of conference materials	Conference organization
	Conference duration	Venue, Catering, Accommodation
	Accommodation types used	Accommodation
Virtual	Time spent online by attendees → Virtual experience design and conference duration	Virtual experience
	Membership distribution	Virtual experience
Hybrid (in addition to the above)	Share of virtual participation	All
	Extra number of staff members	Stakeholders' transport, Accommodation

food—or normalizing the figures against the number of offered meals would reverse this result (Neugebauer et al., 2020). Lastly, a minor difference regards, again for EurOMA, the lower impact of *Conference organization* in those categories driven by resource consumption (e.g., LU and WC), reflecting the effort of its organizers to reduce conference materials as much as possible.

It is worth noting that some previous considerations are valid because the analyzed conferences had almost the same duration—3–4 days, typical in the OM&OR field. Duration could indeed represent a driver of variation, as some stages like *Venue*, *Catering*, and *Accommodation* depend on it. An increase in the conference days would increase both the relative impact shares of these stages and the overall absolute values, even if probably not linearly for *Accommodation* and *Catering*, as many delegates may not be able to extend their stay due to other commitments. Another potential driver not captured above is the accommodation type used by attendees. We had granular data only for INFORMS conferences in terms of the percentage of stakeholders staying in 4-stars and 3-stars hotels and we extrapolated them to EurOMA and POMS, thus not capturing their actual patterns and neglecting other less used accommodation types (e.g., luxury hotels, hostels, rented flats, and so on). Figure S1.1 in Supporting Information S1 shows the ReCiPE indicator results per *guest•night* for different accommodation options modeled in ecoinvent, highlighting the large difference that can arise.

As to virtual conferences, a large variation is visible going from INFORMS 2020 to POMS 2021 and then EurOMA 2021, with the impact contributions of *Virtual experience* and, consequently, the overall indicator results increasing. By analyzing platform analytics data, we found the reason for this in the different amounts of online activity by attendees, with EurOMA attendees being connected in total for ~8.9 h per person and INFORMS ones for ~2.8 h (no granular data for POMS). Surprisingly, this is unrelated to the conference duration: EurOMA lasted half as long as INFORMS (3 vs. 6 days) but its attendees stayed connected for around three times as long. It has probably more to do with how the virtual experience was designed. EurOMA chose a synchronous format with all live-streamed presentations, while INFORMS, due to its larger size and related planning difficulties, opted for an asynchronous format with mostly pre-recorded presentations. This different engagement level should be considered by organizers when planning future virtual conferences. Another driver suggested by Tao et al. (2021) is the geographical distribution of attendees, which can affect the upstream production of energy used in electronic devices (*Virtual experience* stage) and which we did not capture because of the use of globally averaged datasets.

Table 4 sums up the main variation drivers identified in the analysis.

3.3 | Mitigation options and scenario analysis

Apart from shifting to virtual and hybrid formats, previous studies have suggested several mitigation options to make in-person conferences greener (see the last column in Table S1.1). Most have righteously focused on air travel, being the predominant contributor to environmental impacts—van Ewijk and Hoekman (2021) offer a comprehensive overview in this regard. Main options include the shift to landbound transport for closer air travelers (Desiere, 2016; Neugebauer et al., 2020), the optimization of the conference location based on attendees' origins (Jäckle, 2019; Kuonen, 2015), and the implementation of a multi-hub conference with inter-connected hubs in different locations and attendees traveling to the closest hub (Coroama et al., 2012; Klöwer et al., 2020)—see Parncutt et al. (2021) and Tao et al. (2021) for the issue of hub selection. These options can be

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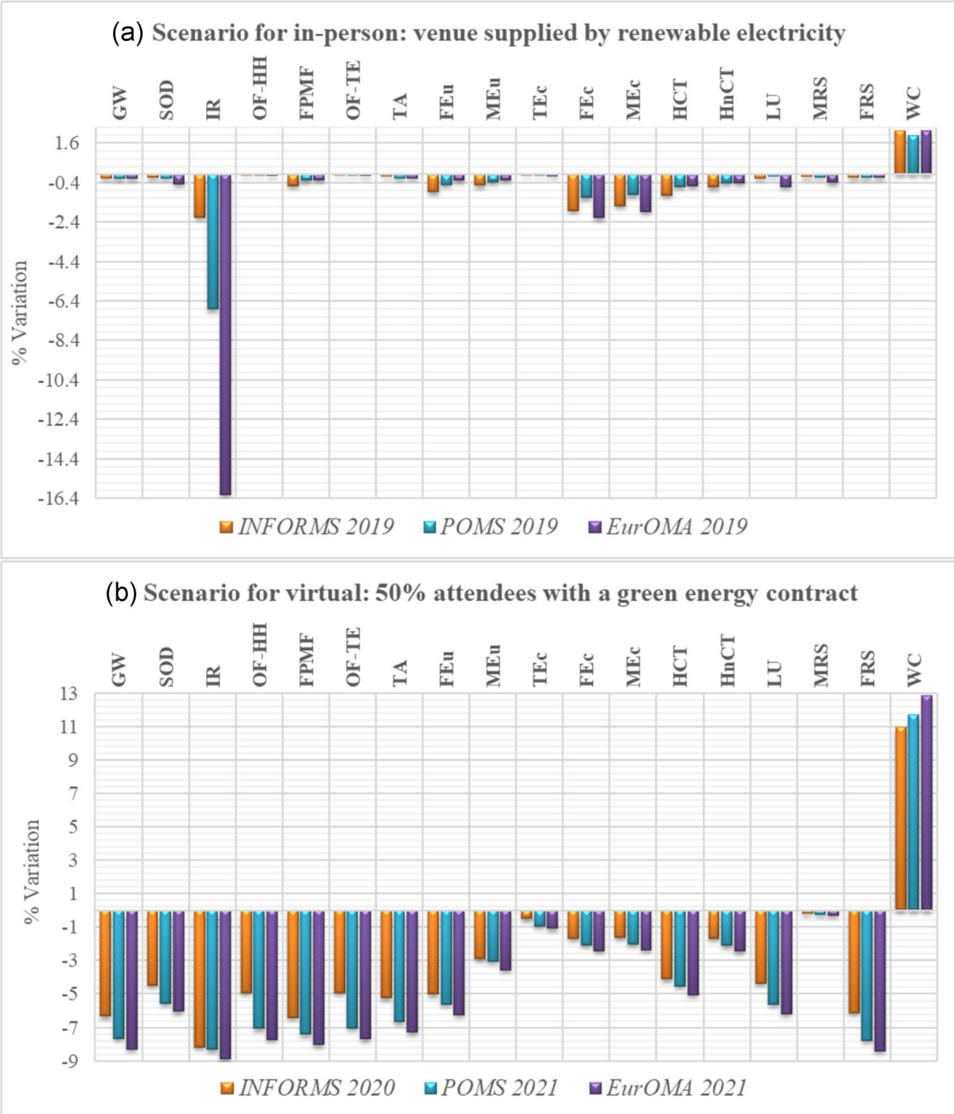

FIGURE 4 Scenario analysis results: (a) scenario for in-person, (b) scenario for virtual. The underlying data for this figure can be found in Supporting Information S9.

theoretically very effective (GHG reductions going from 1% to over 80%), but practically quite difficult to implement for organizers, as proved by their almost null adoption.

Besides travel mitigation, some LCA studies have also assessed some easier options for organizers, such as reducing conference materials or making all meals vegetarian (Hischier & Hilty, 2002; Neugebauer et al., 2020). These measures, though, produce a limited environmental benefit (less than 1% GHG reduction), as our data confirm. Improvements addressing *Accommodation* impacts could potentially be more effective, being the second most impactful stage. Neugebauer et al. (2020), for instance, suggested organizers could commit to partnering with hotels with green credentials, but the associated benefit remains uncertain due to the lack of proper LCI data. Relatedly, Figure S1.1 shows how impacts can change based on the chosen mix of accommodation types. Organizers could therefore incentivize attendees to select less impactful facilities.

Regarding instead *Venue* impacts, our study suggests some novel mitigation options never addressed in the previous literature. First, we have shown, through the INFORMS 2019 case, the substantial benefit of choosing a venue supplied by a biomass-fueled district heating system: 91.4% reduction in the *Venue* per-capita carbon footprint compared to other in-person conferences (−41 kg CO_{2eq}). We assess here, through scenario analysis, another option, namely, the selection of a venue with a green energy contract that purchases electricity only from renewable sources. Since all systems should be optimized if we are to achieve carbon neutrality, we further introduce a mitigation option for virtual conferences, assessing a scenario where 50% of attendees have a green energy contract for their household—that could be rewarded by organizers through ad hoc incentives. The scenario analysis was made possible by some recent datasets introduced in ecoinvent. Results are displayed in Figure 4.

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The in-person scenario (Figure 4a) leads to an average reduction of 0.8% across all categories and conferences. The absolute reduction in the carbon footprint is around 1.9 kg CO_{2eq} per person. The virtual scenario instead (Figure 4b) drives an average reduction of 3.9%, which is greater for EurOMA as the time use of electronic devices was greater. For GW, this means an average reduction of 80 g CO_{2eq} per person. Interestingly, the use of green electricity in both scenarios leads to an increase in the water footprint (+2.1% for in-person, +11.8% for virtual), showing the trade-offs inherent in many technology shifts.

3.4 | Inconsistencies in conference assessments and future developments

Our results extend the knowledge on the environmental impacts of conference formats, main impact drivers, and possible mitigation options, thus providing an updated and comprehensive picture to organizers and society leaders aiming to reduce the impacts of their conferences. In this section, however, we underline several issues that decision-makers and future evaluators should consider when interpreting the results from this and previous studies, and, accordingly, we propose some avenues for future research.

The first group of issues regards *system boundary and allocation*. Several underlying assumptions are made in setting the scope of conference assessments that can heavily affect their results. For instance, all studies allocate the entire travel and accommodation impact to the conference itself. However, it is not uncommon for many attendees—especially distant ones—to combine the conference visit with other activities that would otherwise require separate trips, such as project meetings or family holidays. In these cases, only a share of travel and accommodation impacts should be allocated to the conference, which may drastically reduce impacts. Another issue regards food and other commodities consumption. In this and other studies (Neugebauer et al., 2020), we included only the food consumed at the venue, which is under the control of the organizer. Tao et al. (2021) instead considered the overall food consumption during the conference days, inside and outside the conference. For virtual conferences as well, they included the home consumption of food and energy, obtaining a much larger impact than this study. What should be allocated to conference responsibility is questionable and both approaches have their legitimacy. Tao et al.'s approach probably enables a fairer one-to-one comparison between in-person and virtual formats, but it requires making many discretional assumptions and it unfairly allocates all extra-conference consumption to the conference. Our approach instead allows organizers to focus more on what they can improve, but it probably underestimates conference-induced impacts—especially for virtual formats. A strategy that could turn useful in both cases is to consider the *additionality principle* and compare the selected consumption activities to a business-as-usual scenario—that is, what would have occurred if the conference had not taken place. For instance, Collins and Cooper (2017) calculated the "*net*" ecological footprint of a festival attendee by subtracting their average footprint at home from their footprint at the festival.

The second group of issues regards *format comparison*, with the main one being *format inequivalence*, as already discussed in Section 2.1.1. For a fairer comparison, and more conscious choice of how to organize upcoming conferences, future research should try to assess the social impacts and scientific added-value of different formats and combine them with environmental results by means of more holistic techniques, such as *multiple-criteria decision analysis* or *cost–benefit analysis* (see Andersson & Lundberg, 2013). Another relevant issue regards then *ripple* or *rebound effects* in format shifts (Coroama et al., 2013). Takahashi et al. (2006, p. 288) stated that virtual options "*sometimes change our lifestyle and such changes can induce new environmental loads*." For example, the lower costs of virtual conferences could induce more academics to attend[3] or more conferences to be organized per year, or the saved money and time could be spent on other impactful activities, thus increasing the overall environmental burden. Considering these effects would require an expansion of the system boundary and the design of proper allocation rules. An alternative would be to move from attributional LCAs to *consequential LCAs* studying the effect of several stakeholders' decisions (Palazzo et al., 2020).

All these considerations, however, made us think about the very framing of the problem and the necessity to go back to the basics. Academics do not need conferences per se, they need to network, promote their research, attract feedback, etc., and conferences are just a way to meet these needs aggregately. They bundle a series of services together, such as technical sessions, award ceremonies, and social gatherings, that meet different needs and that could also be provided individually or in different combinations (e.g., seminar series, Ph.D. summer schools). Therefore, the functional unit should not be the organization of a conference, but the delivery of a set of services to meet members' needs within a given time frame. Furthermore, each bundle of services can be provided in in-person and virtual formats, and arguably in-person formats meet some needs better and virtual others. Thereby, in-person and virtual formats should be treated as complements and not as alternatives. The major question for an academic society should then be what the real needs of its members are and what the optimal number, type, and format of activities are to meet them while minimizing environmental impacts. In the end, the sustainability idea is about meeting the needs of stakeholders while remaining within ecological boundaries. This could be done also at the individual level, considering the portfolio of activities to meet the needs of a single academic—Achten et al. (2013) did something of the kind for Ph.D. students. We believe this shift toward a portfolio approach considering the real needs of academics holds promise to move the debate forward and provide academic societies and institutions with the required input to revise their whole business model in a more sustainable way.

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4 | CONCLUSION

This study compared the life cycle impacts of seven real-world in-person, virtual, and hybrid conferences organized by different societies and with different features. The organizing societies belong all to the OM&OR field, which together with the reduced number of cases, may limit the generalizability of the results. Still, our sample presents greater size and heterogeneity than all previous comprehensive LCA studies, which allowed us to uncover significant drivers of impact variation (Table 4). In addition to expected ones, such as the average distance traveled by delegates, new ones were spotted. For in-person conferences, the number of non-local staff members and exhibitors—dependent on society's size and value proposition (e.g., provision of a career fair)—plays an important role in transportation and accommodation impacts. The energy sources and systems used to supply conference buildings instead greatly affect venue impacts. For virtual conferences, the main driver is the time spent online by attendees. Interestingly, instead of a direct consequence of conference duration, this seems to have more to do with how the virtual experience is designed, with synchronous presentations leading to greater engagement than asynchronous ones—~9 h of participation per person at EurOMA (3 days, synchronous) versus ~3 h at INFORMS (6 days, asynchronous).

As to format comparison, our results confirm and extend previous literature. For all societies, virtual conferences were shown to reduce impacts by two to three orders of magnitude across all impact categories: for GW, from an average of 941.9 kg CO_{2eq} per person to 1.0 kg, making them an indispensable option in a serious path toward decarbonization. Put in perspective, the total carbon footprint of the EurOMA 2021 virtual conference was about half the per-capita footprint of an average in-person delegate. The hybrid case study instead, with a composition of 69% virtual attendees, led to a 60% per-capita carbon footprint reduction, less than what was forecasted by previous studies assuming that the farthest attendees shift to virtual attendance (Tao et al., 2021). That cannot be enforced by academic societies without incurring discriminatory behavior, but they might design proper incentives to increase the share of virtual attendees. Beyond format shift, the study reviewed other mitigation options proposed in the literature and provided new ones to tackle venue impacts, namely the selection of a venue supplied by a district heating system (−41 kg CO_{2eq} per person from the INFORMS 2019 case) or with a green electricity contract (−1.9 kg per person from scenario analysis). We also assessed a mitigation scenario for virtual conferences, showing that if half attendees had a green electricity contract, an average reduction of 80 g CO_{2eq} per person would be achieved.

Lastly, to move the agenda forward, the study underlined several inconsistencies that affect present conference studies and proposed some avenues for future research. The most promising one, in our opinion, involves a radical change in focus while investigating the environmental impacts of scientific activities. For the environmental optimization of single conferences, studies are converging toward the multi-hub format (Klöwer et al., 2020; Tao et al., 2021; van Ewijk & Hoekman, 2021). However, do we need those conferences in the first place? The core role of an academic society is arguably not to organize a conference but to meet its members' needs, including the need to network or disseminate research. On the one hand, conferences are not the only way to meet these needs (e.g., seminar series), and on the other, different formats of communication (i.e., in-person vs. virtual) meet various needs differently. Therefore, embracing a portfolio perspective, academic societies should first understand the needs of their members and then identify the optimal number and format of conferences or other activities to meet those needs while minimizing the overall environmental impacts.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are either available in the supporting information of this article or available from ecoinvent and Agri-footprint databases. Restrictions apply to the availability of these latter data, which were used under license for this study. These data are available from the authors with the permission of ecoinvent and Agri-footprint or directly from the third party.

ORCID

Antonio Cavallin Toscani https://orcid.org/0000-0001-6245-9843

NOTES

[1] Some academic conferences comprise exhibition spaces where organizations can promote their products/services. Some conferences, especially in the United States, also involve career fairs that serve the purpose of matching recruiters and job seekers (mostly academic institutions).

[2] To facilitate understanding, values in the collection sheets refer to the entire conferences and not to the functional unit of an average conference participant. To move from total to in-person figures, values need simply to be divided by the number of attendees.

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[3] This was not the case in our conferences, probably for the high prices set for virtual formats. Virtual conferences from other fields showed instead a great increase in attendance thanks to their better accessibility (Skiles et al., 2022).

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