Mediators in Systems-of-Systems and Ecosystems: A Systematic Literature Review and Conceptualization

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ABSTRACT

In most systems-of-systems (SoS) and ecosystems, peer-to-peer relations are insufficient to provide the desired emergent behavior, but the support of mediators is necessary. Mediators are elements that facilitate the collaboration between the constituents of the SoS or ecosystem, without having a role outside it. The topic has previously been studied in the SoS field, mainly from a software engineering perspective, and separately also in research on software, business, and innovation ecosystems. This paper presents a systematic literature review on mediators across scholarly work in SoS as well as ecosystems. It identifies mediator functionality and implementation concerns, and discusses alternative terminology. Based on findings from the literature, a suggestion for an improved conceptualization is presented, which also includes the information, processing and interactions involved in the mediation.

CCS CONCEPTS

• **Software and its engineering → Software architectures**.

KEYWORDS

Mediators, Systems-of-Systems, Software Ecosystems, Business Ecosystems, Innovation Ecosystems

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1 INTRODUCTION

In a *system-of-systems* (SoS), independent *constituent systems* (CS) choose to collaborate to achieve benefits that cannot be reached by them individually [22]. CS have not only operational independence but also managerial independence [27]. Hence, the organizations involved with the SoS and individual CS must also collaborate to make the SoS effective. This organizational collaboration has been studied from a general perspective in the field of *business ecosystems* (BECO) [35], and somewhat more specialized in the context of *innovation ecosystems* (IECO) [20] and *software ecosystems* (SECO) [32].

SoS and the various flavors of ecosystems often coexist in the same practical situation. In particular, the connections between CS in an SoS are normally created through software-driven communication, which relies on a SECO. The incentives for collaborating in the SoS are captured by looking at it as a BECO, and the constant evolution of the SoS can be explained through concepts used when describing IECO. However, the fields are as of today mostly researched in separate communities, and there are reasons to believe that both perspectives would gain from increased cross-fertilization.

One particular aspect the fields have in common is the acknowledgment that collaborations rarely appear out of nothing. Instead, the organized collaboration in an SoS or an ecosystem can often be made more efficient and effective if the independent CS are complemented with elements that take on a dedicated role of facilitating the interactions among CS. Since these elements can be thought of as sitting in between the CS, they are sometimes referred to as *mediators* (from the Latin word "medi", which means "middle".) However, the exact role and function of mediators are often unclear in the literature, as is the level of abstraction at which a certain mediator is used. The terminology is also inconsistent, and it is common to use other terms like intermediary, broker, or facilitator.

The purpose of this paper is to provide a clearer conceptualization of mediators, to make them easier to work with when developing an SoS or ecosystem. Since the concept lies at the intersection between SoS and ecosystems, it will also contribute to bringing the fields closer to each other.

The research consisted of two parts. First, a systematic literature review (SLR) was conducted on the use of mediators in the fields of SoS, BECO, IECO, and SECO. The data collected from the literature, together with existing theories, was then used to derive a new characterization of the mediator concept from different perspectives, some of which have not been emphasized in prior research.

The remainder of the paper is structured as follows. In Section 2, the related work is summarized. In Section 3, the conduct of the SLR is described, which is followed in Section 4 by a presentation of the main findings from the literature. In Section 5, the results are put in perspective, and in the final section, the main conclusions are summarized together with some ideas for future work.

2 RELATED WORK

This study is a survey of the existing literature on mediators in SoS and ecosystem research and, based on that, an analysis and conceptual description of mediators. Therefore, the related work of the study as a whole consists mainly of prior literature studies on

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mediators and conceptual frameworks that have previously been proposed. This section presents what has been found in these two categories.

2.1 Prior Literature Reviews

Garces et al. investigated the notion of mediators in software-intensive SoS [17, 18]. Based on a literature survey resulting in only four papers, they constructed a taxonomy of twelve types organized into three categories: communication (pipe, collaborator, distributor, router); conversion (filter, wrapper, adapter, data fusion); and control (monitor, analyzer, planner, executor). These are described very clearly using SoSADL [40] models, and thus provide an excellent starting point.

However, the study also has limitations in the kind of mediators considered, and its assumption of a static structure. The focus is on software, with mediators seen as "architectural elements that enable interaction between software entities" [17] and as "first-class software entities" [18]. There is a clear inspiration from the mediator pattern used in software engineering, thereby putting the concept on a lower level of abstraction and closer to a software implementation than it needs to be. Mediators for organizational or ecosystem situations are not as clearly described, nor is the motivation for introducing mediators always explained. There is also no clear connection to the independence of CS, and the suggested patterns seem to apply to any software system, SoS or not.

McPhillips provided a review of the IECO field [31]. As part of her investigation, an extensive (albeit not systematic) literature review was conducted, with a focus on groups of agents assembled in clusters. These clusters are distinguished through geographical proximity, but their performance can improve by having mediators to facilitate communication and collaboration.

Axelsson reviewed SoS patterns [7]. The patterns were identified on the levels of the SoS as a whole, on constellations [6], and internally in CS. Many of the identified patterns also include some kind of mediator.

2.2 Conceptual Frameworks

A very influential theoretical framework was proposed by Gould and Fernandez [19]. They discuss brokerage in transaction networks that consist of a set of interrelated actors. A broker is then an actor situated between two otherwise unrelated actors. The actors are further subdivided into groups (according to some unstated criteria). Based on the groups the two actors a, a' and the broker b belong to, five different types of brokers are possible:

- *Coordinator.* a, a', b are all in the same group, and the broker acts as an internal coordinator.
- *Cosmopolitan.* a, a' are in the same group, but b is outside of the group, acting as an outsider consultant.
- *Gatekeeper.* a is in one group, and a', b in another. The broker acts as a gatekeeper to the second group.
- *Representative.* a, b are in one group and a' in another. The broker acts as a representative of a' in the group of a.
- *Liaison.* a, a', b are all in different groups, and the broker serves as the liaison between the groups.

The categorization is relevant to SoS and ecosystems since there are different types of groups present. This includes the elements of the SoS vs. the elements outside, who could join the SoS but have not yet done so, and the elements in a certain constellation [6].

However, the conceptual framework is also limited in that the relations are static, and hence mediators that create new relations cannot be modeled. Such a dynamic structure is a prominent feature of SoS. It further does not distinguish between different kinds of relations and does not consider non-binary mediation. The latter is important since some mediators are introduced to aggregate a holistic view of emergent properties and make it available to CS.

This paper aims to expand on previous reviews to cover and align SoS and ecosystems, rather than treat them separately. With inspiration from how Gould and Fernandez structure their characterization of broker types, a new conceptualization is sought that gives a broader picture of mediators in SoS and ecosystems.

3 SYSTEMATIC LITERATURE REVIEW

It will now be described how the SLR on mediators was carried out. First, the type of study is classified and then the strategy for searching and screening the literature is presented. Finally, the approach for data extraction and analysis is outlined before, in the next section, proceeding to the findings of the review.

3.1 Study Classification

This study can be characterized as a meta-synthesis [45]. Its purpose was to systematically review the literature to explain the concept of mediators. It was based on qualitative primary studies and performed a qualitative analysis based on the synthesis of numerous studies to derive a conceptualization that is applicable throughout the field of study.

3.2 Search Strategy and Screening

Scopus[1] was used for the literature search since it is the largest database of its kind and is known to cover much of the relevant literature on SoS and ecosystems. The search string was:

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TITLE-ABS-KEY(mediat* AND (system-of-systems OR
((business OR innovation OR software) PRE/0 ecosystem))
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The search string means that the search was carried out on title, abstract, and keywords. Matching studies should mention the term "mediator" (or one of its variants, such as "mediation", or "mediating".) It should also mention either "system-of-systems" or one of the terms "business", "innovation", or "software" directly preceding the term "ecosystems." Note that Scopus automatically includes plurals and some variants of the search terms, such as "systems-of-systems", "systems of systems", and "ecosystems".

The search was carried out on April 24, 2023, and resulted in 121 studies. These were imported into the Covidence[2] SLR tool, which is essentially a database for bookkeeping during the following steps of processing. The studies were first screened based on title, abstract, and keywords and then on the full text. During the screening, a total of 79 studies were removed, and the main reasons were: outside study scope; non-English; proceedings volume (rather than an individual paper); full text not available; the term mediators just mentioned briefly; or the term was used in a different meaning.

[1] https://www.scopus.com
[2] https://www.covidence.org/

In the last category, there was an interesting subclass. Many studies on ecosystems were statistical analyses of data collected through surveys or similar. These studies often apply a statistical analysis technique called mediation, and the inclusion of the term in this sense made them appear in the database search. However, since these 33 studies did not discuss mediators as an entity in the SoS or ecosystem, but just as part of the statistical analysis, they were excluded.

In total, 42 studies were included in the further steps [1, 2, 4, 5, 9, 11–18, 21, 23–26, 28–31, 33, 34, 36–44, 46–54].

3.3 Data Extraction and Analysis

Once the screening was completed, a data extraction form was created in Covidence. Apart from various data about the studies, such as publication year, authorship, and area of study (SoS, BECO, IECO, SECO), the main fields in the form related to:

- What definitions of mediators are used?
- What alternative or related terms to mediators are used?
- What functionality do the mediators provide?
- How are mediators implemented in applications?
- In what application domains are mediators used?

After completing the extraction, the collected data for each of the questions was cross-read between the studies, using a dialectic hermeneutic approach [10]. What this means in practice is that the researcher needed to apply a certain element of interpretation while taking into account the contextual setting of the studies. This was a consequence of the broadness of the topics in the studies, as well as the lack of common terminology.

4 FINDINGS FROM LITERATURE

The findings from the literature will now be summarized, starting with some general characteristics of the literature body in terms of publication statistics, authorships, and methods used. Then, the application domains are presented, followed by the usage of definitions and alternative terminology. The various functions that the mediators can provide are discussed, and finally, some observations are made on the implementation of mediators.

4.1 Publication Statistics

Figure 1 shows some statistics of the studies. The Venn diagram indicates how many studies were found in each of the four fields of SoS, SECO, BECO, and IECO. The classification is based on the author's interpretation of the studies, and some of them fall in the intersection between the fields. The histogram shows the number of publications per year, in total, and subdivided by research field.

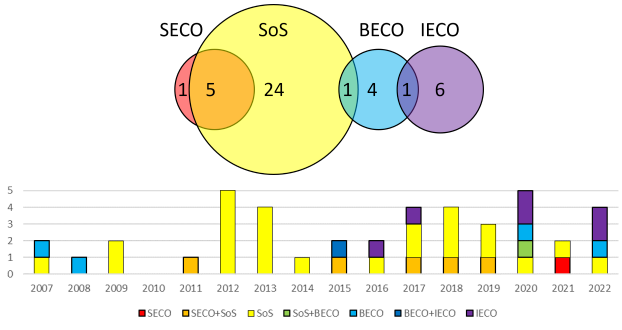

Figure 1: Number of studies per research field and year.

Some conclusions can be drawn from this figure. The publications are roughly equally divided between SoS and ecosystems (although the latter is subdivided into smaller fields). There is an overlap between the fields, and primarily between SoS and SECO. Finally, there is a small but steady flow of publications over time, with no other clear trends.

The 42 studies had a total of 108 unique authors. Of these, 17 authors are involved in more than one study, and a closer analysis reveals that there are in the SoS field five clusters of studies each centered around a single author. These clusters are Oquendo and 3 coauthors [17, 18, 40–43]; Nativi and 14 co-authors [9, 12, 30, 39, 53]; Preden and 8 co-authors [38, 44, 46, 51]; Axelsson and 2 co-authors [4, 5, 49], and Moschoglou with 3 co-authors [36, 37]. These five nonoverlapping clusters of in total 35 persons have thus produced 20 of the 30 SoS studies. The other 73 authors are only involved in one study each, and thus ecosystem publications are more scattered.

The research methods vary between fields. In SoS and SECO, design studies involving the development of some artifacts are common. In SoS and BECO, there are some theoretical studies without relation to any empirical data or real application. In IECO, action research and case studies are common, which are also used in BECO.

4.2 Application Domains

Almost all the studies relate to at least one application, and they are spread over a broad range of domains: geographical information systems (GIS) [9, 12, 23, 30, 39, 53]; energy [16, 46]; sensor networks [13, 33, 36, 38]; defense [44, 50]; crisis management [17, 18, 40, 41, 54]; construction [48]; transportation [1, 14] with an significant special case of vehicle platooning [4, 5, 42, 43]; industrial production [24]; information and communication systems [11, 15, 26]; and social and health aspects [18, 21].

4.3 Definitions and Alternate Terms

A general observation of the literature is that the term mediator is rarely defined with any precision. Instead, each study typically focuses on one or a few of many possible characteristics, such as a particular functionality. Some highlight the mediator's role in facilitating better collaboration [2, 5, 49]. Others emphasize their roles in transactions [1], in particular when it comes to the exchange of information [24, 33, 38] and knowledge [29]. Different mediator functions will be studied in more detail in the next subsection.

In addition to mediators, several alternative terms are used. The most common is "broker", which appears both in IECO [2, 29, 34], and the intersection between SoS and SECO [9, 12, 30, 39, 53]. In the latter, it is considered a central computer node responsible for a multitude of services such as discovery, composition, and interoperability. Other proposed terms are "catalyst" and "intermediary" [2]. For different roles in the distribution of resources in an SoS architecture, the terms "coordinator" and "negotiator" are suggested [13]. One further term is "proxy", which is a mediator acting on behalf of a cluster of actors [31].

A variation between studies is that some refer to "mediators" and others to "mediation", "mediating processes", or similar. The "mediator" is then the actor, "mediating" is the process carried out by that actor, and "mediation" can be seen as the capability of the actor. This difference is more subtle than it can appear at first. Although it is possible to have an actor that carries out the mediation process, it is also possible to handle it in a distributed way. These alternatives will be revisited in Section 4.5 below when discussing the implementation of mediators.

4.4 Functionality of Mediators

Most of the studies discuss functions that a mediator performs but the functions are typically presented concretely in the context of a particular application. To distillate what generic functions these are examples of often leaves room for interpretation. A further complication is that the mediating actors described commonly combine several functions (see, e.g., [25]), and sometimes these are not properly distinguished from each other.

In this subsection, some recurring functions are discussed. They are grouped into four categories, as illustrated in Figure 2. The figure uses a notation inspired by [19] (see Section 2.2), where A and B are two actors, M is a mediator, and S refers to a larger system or group that includes some of those entities. The first category is *communication* and contains mediators for general information transfer. The second is *networking*, which provides services that mediate the structure of the SoS or ecosystem. The third group focuses on *collaboration* aspects. Finally, the fourth group deals with *trans-ordinal* effects. In what follows, each type of mediator is presented in more detail. The four groups are then revisited in Section 5.2 to discuss their key differences and similarities.

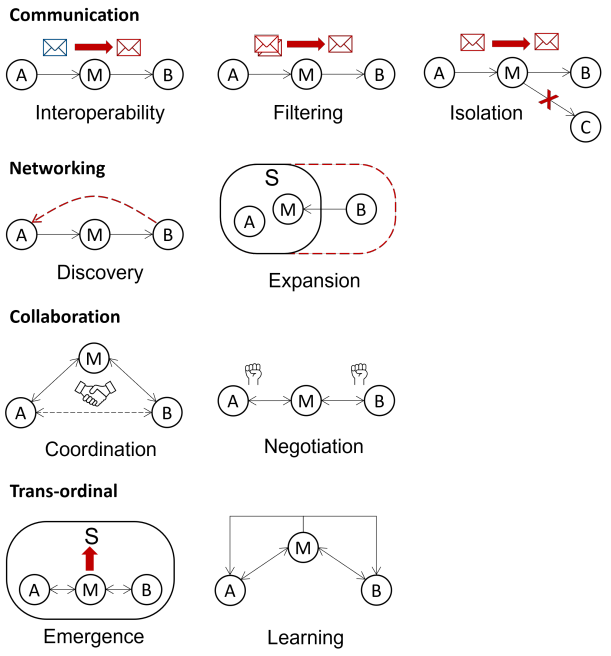

Figure 2: Functionality of mediators.

4.4.1 Interoperability. The most common form of mediation in the literature is interoperability. It is concerned with the fact that different actors may use different information representations, which leads to difficulties in communication and collaboration. Although interoperability is a general concept applicable between any two actors, it is foremost used in technical and software systems in the SoS field, and less in the others. Prime examples can be found in the studies on GIS, where a global SoS is built for sharing geographical data on many formats [9, 12, 30, 39, 53]. The principle solution is data transformation [50], which in general requires ontological information about the different representations [15, 36, 37].

4.4.2 Filtering. In an SoS, a lot of information can be passed around, but not everything is of interest to all actors. Filtering can be used to suppress undesired information as part of subscribing to services of a communication mediator, to reduce the burden of the actors receiving it [38, 51].

4.4.3 Isolation. Suppressing information is also relevant for privacy or security reasons, keeping control of which actors are entitled to what information [14, 25]. Functionally, this is similar to filtering, but the purpose is different. While filtering is based on what the receiving CS would like to know, isolation concerns who the providing CS believes is entitled to access the information.

4.4.4 Discovery. In a large network of actors, a key problem is finding out which actors should be connected. Often, mediators are used that provide catalogs of the services different actors can provide [9, 12, 30, 39, 53] and brokerage of connections to resources in general [13, 52]. The discovery can be dynamic, as in the case of match-making for vehicle platooning [5] or for finding and purchasing services in an ecosystem [1, 24, 29].

4.4.5 Expansion. The set of elements in an SoS or ecosystem is not static. The value of being a member often increases with the network size, and hence there is an incentive for expanding the SoS. This is discussed in the context of enhancing the reach of the IECO [21, 29, 31], but is equally relevant in SoS or other ecosystems.

4.4.6 Coordination. When the CS of an SoS come together in a constellation [6] to achieve a joint capability or carry out a process, there is often a need to coordinate their individual actions and interactions [48, 52]. Some refer to this as orchestration [9], and it requires communication around the capabilities, plans, and needs of the actors [4].

4.4.7 Negotiation. Coordination assumes some agreement between CS on what to achieve, but due to the independence of CS, their interests are not always aligned. Such conflicts may need to be resolved by a mediator [29]. One area of conflict is the distribution of the gains and costs related to collaboration [5, 14].

4.4.8 Emergence. Most of the functions mentioned previously take place between individual actors. However, mediators can also be more explicitly used for ensuring the desired emergent effects of an SoS as a whole [40] through symbiosis [14]. This can be achieved by constraining local interactions between CS [41, 43], or improving shared situational awareness [38]. Similar ideas are also described in IECO, where mediators are used to bring system-level policy

implications [21]. Since emergent effects are on a higher, transordinal level of abstraction than the element level behavior [42], this requires also semantic mediation [54].

4.4.9 Learning. An actor can enhance its capabilities by learning new things, which may not help immediately but can prove useful later on. Mediators have been proposed to enhance actor learning both in IECO [21] and also on a technical level for inferring ontologies in an SoS [23].

4.5 Implementation of Mediators

In the literature, different suggestions are made regarding the implementation of mediators. Many of the studies apply a design science research approach (see Section 4.1 above) and the description of implementations is dominant in these. However, in most studies, a solution to a particular problem is presented, but rarely are alternative solutions or the motivations for the choices discussed in any detail.

4.5.1 Centralized. A key implementation decision for mediators is whether it should be centralized, decentralized, or somewhere in between. A completely centralized implementation of a mediation functionality means that there is a separate system within the SoS, purposefully designed for mediating in this context and hence not an independent CS [44]. In certain situations, this is reasonable, such as when there is a need for a discovery or match-making service that can assist in finding new relations to any CS in the SoS [4]. The mediator thus needs to have a complete picture of which CS exist and their characteristics. The apparent drawback is the reliance on a central node in the network, both from a resilience perspective and for the disproportional influence given to this actor.

4.5.2 Decentralized . The opposite end of the scale is a completely decentralized peer-to-peer solution [26], where the CS interact directly with each other. The mediation is then handled by modifying all CS so that they have a common understanding of certain rules and assumptions on which the SoS is built. Commonly, this information is provided to the CS in the form of a shared software library or middleware [38, 44] which they can integrate into their own software. In essence, the computing power is provided by the CS, but the logic is common to the SoS as a whole. Although not mentioned in any of the studies, it is also worth noting that an alternative to a shared software library is a common requirements specification. In a case where CS are heterogeneous or when non-digital communication is used for mediation, this may be a preferable solution for implementing decentralized mediation.

4.5.3 Partially Centralized. There are also possible solutions that fall in between the two extremes. Sometimes, it is the ordinary actors that mediate in an ecosystem without having formally been appointed to this role [29]. There could also be multiple dedicated mediators who take on the same role, but which are still separate entities from the CS [24]. Each actor would then interact with a mediator, and the mediators are connected in a network.

4.5.4 Orchestration and Choreography. The implementation of mediating mechanisms is sometimes based on the established toolbox of service-oriented architecture (SOA) [12, 53]. In particular, there are references to the SOA concepts of orchestration [9, 24] and choreography [24], which have similarities with the centralized and distributed implementation.

4.5.5 Ontologies. Looking into the special case of interoperability mediators, a variant of the distinction between centralized and decentralized also appears on the data level. A centralized approach is to provide a common reference ontology. The translation proceeds by first mapping the input data to the reference ontology [15, 50], and then mapping the reference ontology to the output data format. These mediators provide translation services between different protocols or data models.

A decentralized alternative is to provide a distinct translator for each pair of protocols or models. Which alternative to select depends in part on the number of protocols to be handled, where the number of decentralized mappings would grow with the square of the number of protocols. On the other hand, the centralized approach, while linear in the number of protocols, has a starting cost in the development of the reference model. There have also been suggested alternatives, where the protocol translators are generated automatically from an ontology when a need appears [23].

Regardless of which approach to select, ontologies play a key role in providing the meta-information on which communication is based [52]. These ontologies need to include representations of the services provided by different CS [36, 37], but also the representation of other kinds of information handled by the actors.

4.5.6 Management and Governance. All mediation solutions share the characteristic that some effort needs to be made to put the solution in place. This could be creating a centralized mediator, or developing the middleware software used in a decentralized approach. Therefore, key questions become how to organize this effort [5]. Should it be carried out by one actor, or a consortium of actors? If it is to be one actor, which of the stakeholders in the SoS is most suitable? How should that actor be compensated for its efforts? These decisions call for management and governance structures, which can be handled bottom-up [14] or through a more or less open consortium [24].

4.5.7 Passive Mediation. So far, the discussion has been on active mediators. However, parts of the literature also discuss mediation through passive objects. These boundary objects [48] could be in the common environment of the SoS, which the actors can modify to leave stigmergic information that can later be discovered by other actors [28]. Epistemic objects that result from knowledge work in a BECO are also reminiscent of this [16], as are the technology-mediated interactions observed by [47].

5 DISCUSSION

In this section, the findings from the literature review will be discussed and put into perspective. To start with, the results from this broader review of both SoS and ecosystems will be compared to the previous review on SoS mediators with a software emphasis. Then, some directions are drawn up in which the results could be generalized, to eventually provide a better conceptualization of mediators. Finally, the validity of the study's findings is questioned.

5.1 Comparison to Existing Taxonomies

It is interesting to compare the list of mediator functions elicited from the broad literature on SoS and ecosystems with the taxonomy for SoS mediators proposed by Garces et al. [17, 18] (see Section 2.1.) Interoperability is related to the "adaptor/translator" and "wrapper" solutions in their taxonomy; filtering has a direct correspondence to their "filter" mediator; coordination relates to "planner/decider" and "executer/actuator"; emergence is partly related to "aggregator"; and learning has some relation to "analyzer". However, some of the mediators identified in this study are missing in their taxonomy, in particular discovery, expansion, and negotiation. A possible explanation is that these functions are on a higher level of abstraction and map less clearly to a pure software view of SoS.

The findings can also be compared to the framework suggested by Gould and Fernandez [19]. Their focus is on the structural positioning of mediators. However, the grouping they use as a foundation is not as evident for the mediator types discovered in the literature. In particular, some mediators, such as those for discovery and expansion, have as their purpose to change the grouping, and this structural dynamics is not covered in their framework. Furthermore, not all mediation is transactional. Coordination, negotiation, and learning can be expected to be more of an ongoing process with multiple bidirectional transactions taking place as part of it.

5.2 Dimensions of Mediation Functions

Despite the evident gaps in prior conceptual descriptions of mediators, this should not be seen as a discouragement to search for a general approach. Having a clear terminology and structure of a concept like mediators would be helpful in many respects. First of all, it would help practitioners understand what kind of mediators are best suited to solve their problems. It is thus a way of describing parts of the design space to be explored. Secondly, it would provide a clearer language for describing cases and applications of SoS and ecosystems, making it easier to compare the types of mediators used and elicit empirical knowledge. Finally, a theoretical model would help identify new types of mediators that have not been reported in practice but that could solve important problems.

A categorization of mediators would need to look at several orthogonal dimensions. Based on the literature findings, some tentative axes can be discerned. These include what *type of information* is exchanged through the mediators; how the information is *processed*; and the *interaction* aspects of the mediation. The proposed dimensions should be seen as a complement to the Gould and Fernandez framework [19] (see Section 2.2), which emphasizes the dimension of structural placement of the actors.

These aspects will now be discussed a bit more in detail, based on the four groups of mediators shown in Figure 2. An overview of the discussion can be found in Table 1.

5.2.1 Communication mediators. These are essentially mapping information from one representation to another. The generic types do not put any limits to what type of information they process (although a concrete usage will apply to particular information sets.) The mediation is transactional in the sense that each message can be processed separately using a bounded process. More specifically, *interoperability* mediators translate messages by mapping from one ontology to another. *Filtering* mediators remove information, which can be seen as mapping from one ontology to another smaller one. *Isolation* mediators also remove information, but do this completely for certain actors and not at all for others.

5.2.2 Networking mediators. These process particular kinds of information that describe actors, and their relations and properties. They perform transactional processing, which ends when the actors have been provided with enough information to alter their relations. In the case of *discovery*, the mediator would receive information describing a desired relation, and process that information using its knowledge about the current network members to find an appropriate agent to form the new relation with. In the case of *expansion*, the mediator would process information about a candidate actor and determine if it is to be included in the network.

5.2.3 Collaboration mediators. In general, these are not transactional but operate as part of an ongoing process. This also means that the mediator will form a constellation with the involved actors for as long as needed, and engage in multiple bidirectional information exchanges with them. The information processed is related to the actors and includes abstract and complex concepts such as incentives, plans, and capabilities. This information is closely related to what it means for a CS to be independent [8]. A *coordination* mediator would try to find a distribution of roles among the actors in the constellation so that the overall goals are achieved. A *negotiation* mediator would try to find compromises that align the incentives of each actor so that everyone is satisfied and willing to be part of the constellation.

5.2.4 Trans-ordinal mediators. These handle state-oriented data and focus on behavior, i.e., how states change over time, making them continuous rather than transactional. They are trans-ordinal since they map data from a lower level of abstraction to a higher one. Higher abstraction means a reduction of information, hence the dynamics at the higher level are in general slower than on the lower level. Therefore trans-ordinal processing typically requires aggregation of data over time or from multiple agents. The *emergence* mediators aim at ensuring some system-level abstract properties. They achieve this by influencing the actors' behavior in processes similar to coordination or negotiation. However, the difference is that the mediator must have models or measurements of the system-level properties and use those as a basis, whereas collaboration mediators could work on only the level of abstraction used by the individual actors. The *learning* mediators gather data over time, try to see patterns in the data, and inform the actors about those patterns to improve their behavior.

5.3 Agents and Abstraction

When analyzing the underlying dimensions of the mediator types found in literature, two aspects became apparent. The first is the need to have an improved understanding of the actors between which the mediation takes place. A key characteristic of the actors that represent the CS in an SoS or ecosystem is their independence, but to do anything meaningful with that notion, it has to be described more precisely. One model that has been proposed for this brings up the notions of perception, world models, expected utility, decision-making, and capabilities [8]. These elements are implicitly present in the identified list of mediator types. For instance, the

Category	Mediator	Processing	Information	Interaction
Communication	Interoperability	Translate between ontologies	Any	Transactional
	Filtering	Remove information based on relevance		
	Isolation	Remove information based on authority		
Networking	Discovery	Find new relations	Relations	
	Expansion	Add new members		
Collaboration	Coordination	Define roles	Capabilities, incentives	Continuous
	Negotiation	Align incentives		
Trans-ordinal	Emergence	Control system level state	States	
	Learning	Find behavioral patterns		

Table 1: Classification of mediators based on processing, information, and interaction.

communication mediators relate the actors' world models and the collaboration mediators deal with incentives that can be expressed in terms of expected utility functions. A possible extension of this work is to start from the agent model and investigate what theoretical mediation functions can be deduced from it. This can then be validated based on findings in literature and case studies.

The other aspect is that additional focus needs to be put on abstractions. This is highly relevant for many of the mediator types, such as the trans-ordinal ones that explicitly deal with relations between abstraction levels, or interoperability that is ultimately a consequence of actors that independently choose the ontology that can form a basis for their own information processing needs. Since these needs will differ, they will end up with different ontologies and thus a misalignment. It is worth exploring further how mediators can be described in terms of which abstractions they use.

5.4 Validity

Some notes on the validity of the results are in place. The first concern is the identification of primary studies. Only one database was used, albeit the largest available and one known to cover a large portion of the relevant literature. There is thus a risk that some relevant studies were missing in the search results. Also, the screening and extraction were carried out by a single researcher, and hence there is a risk that further relevant studies or data therein were erroneously rejected.

A further difficulty is the use of terminology. This study focused on mediation, but as was shown in Section 4.3, many other terms are in use for much the same concepts. A similar argument can be raised related to SoS and the different variants of ecosystems. Many publications are related to these classes of systems but use different names, such as cyber-physical systems or the Internet of Things.

The greatest threat is still the diverse nature of the publications, which necessitated the dialectic hermeneutic approach to analysis. A lot of interpretation was required to be able to draw parallels between the different studies, in particular for those that come from such diverse domains as technically oriented SoS and the organizationally focused IECO or BECO.

All in all, no claims can be made that this study presents the full body of knowledge or all possible aspects related to the topic. The results are instead a rich set of examples of mediators from a broad sample of the literature, and the identification of several principles for mediator functionality and implementation, that are likely to be useful as the basis both for practical work on mediators as well as future research.

6 CONCLUSIONS AND FUTURE WORK

In this paper, a systematic literature review on the concept of mediators has been presented. The review is broader than previous research, in that it covers both SoS and various kinds of ecosystems. In total, 42 different studies were reviewed. These primary studies discuss a wide range of usages of mediators across many application areas. They provide functionality related to interoperability, filtering, isolation, discovery, expansion, coordination, negotiation, emergence, and learning. The implementation issues focus on centralized vs. decentralized solutions, and the use of ontologies. It also touches upon management and governance questions.

There is wide recognition that mediators play an important role in both SoS and ecosystems. Despite this, it is surprising to see the relatively small number of studies discussing the topic. Given that the annual output of SoS research is about 500 articles [3], only around 1% give some significance to mediators. There is thus clearly room for further research. One important direction this could take is to develop and validate a general theory of mediation, and this paper could serve as a stepping stone for further research in that direction. Future aspects to investigate could be based on an agent model of independence, or on what types of abstractions mediators use. A final issue of great practical importance is the lifecycle management of the mediators, and the associated governance structures needed in an SoS or ecosystem.

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