A design method for collaborative systems of systems applied to Metropolitan Multi-Mode Transport System

Pontus Svenson , Frida Reichenberg, and Jakob Axelsson
RISE Research Institutes of Sweden
{pontus.svenson, frida.reichenberg, jakob.axelsson}@ri.se

***Abstract*— Systems of systems arise when independently owned, operated and developed systems can achieve mutual benefits by working together. In collaborative systems of systems, there is no directing entity that instructs others how and when to collaborate. Instead, the collaboration relies on independent decisions by the constituent systems to form collaborating constellations, and the benefits are emergent properties of this. In this paper, we describe a design method for engineering collaborative systems of systems. We apply the method to the design of a collaborative system of systems for mobility in a rural setting close to an urban area and to truck platooning.**

Keywords—Collaborative system of systems, SoS engineering

I. INTRODUCTION

Systems of systems (SoS) arise when independently owned, operated and developed systems can achieve mutual benefits by working together [1], [2]. The participating systems are called constituent systems (CS). Systems of systems are distinguished from integrated systems by this independence. In some cases, the system of systems is nevertheless controlled by a single entity – so-called directed systems of systems. To engineer a directed system of systems, the developing organization needs to be aware of the capabilities of the participating systems and can then direct their use to solve the need for which the system of system was created.

The distinctive feature of a collaborative system of systems is that there is no directing entity that instructs others how and when to collaborate. Instead, the collaboration relies on independent decisions by the constituent systems to work together, and the benefits are self-organized or emergent properties of this.

How, then, can we facilitate such self-organization? A collaborative system of systems will often require additional components that provide information and other services to the constituent systems. Such components are called mediators [3]. In addition, the collaboration relies on agreements and deals between the participating organizations. How can we determine what mediators and what agreements are necessary in order to create a collaborative system of systems that helps solve a certain problem? Any system of systems also requires standards that facilitate communication in an interoperable way. These standards need to be defined and updated.

In this paper, we describe a design method for engineering such systems of systems. The method starts from a description of the problem area which we wish to address and a list of possible stakeholders and their requirements on the solution. The requirements are interpreted as values which the stakeholders desire from the solution. It then iteratively develops a more and more refined description of the system of systems by analyzing how these values could be realized and what additional components and agreements must be added to the system of systems.

We apply the method to the design of a collaborative system of systems for mobility in a rural setting close to an urban area. While traditionally mobility-as-a-service (MaaS) solutions for such problem domains are designed as a directed system of systems or even an integrated system, where one actor (*e.g.,* a public transport authority) contracts others to deliver services, we argue that designing it as a collaborative system of systems provides for increased efficiency, extendibility and availability.

To show the generalizability of the method, we also apply it to vehicle platooning. For this case (as well as others not presented in the paper) the design method reproduces results from earlier designs.

The paper starts with a section on systems of systems, focusing on the need to create constellations. Next, we describe how a constellation performs an intervention, and hence the system of system must be designed to enable this. Section IV describes an iterative method for designing a collaborative system of systems, which is then applied to examples. We end with a summary and suggestions for future research.

II. SYSTEMS OF SYSTEMS EXIST TO CREATE CONSTELLATIONS

A system of systems is meant to enable the solution of problems for which collaboration between independent systems is needed. In addition to the constituent systems that are meant to together provide this solution, the system of systems also needs to have mediators and infrastructure elements [3]. Mediators are elements that facilitate the collaboration and have no independent purpose outside of the

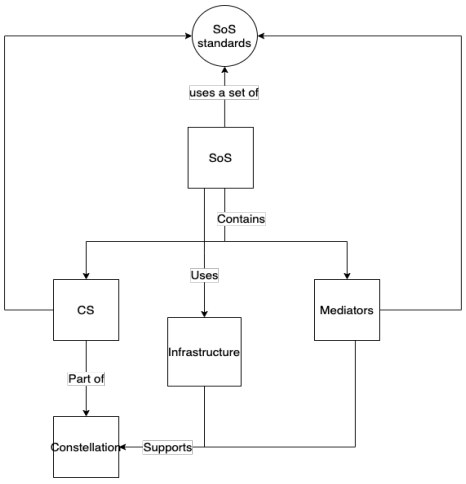

Fig. 1. Components of a system of systems.

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system of systems, while infrastructures are facilitating elements that also have a reason to exist outside of the system of systems. Fig. 1 shows the components of a system of systems. All of these have to be aware of and conform to a set of SoS standards.

Each element of the system of systems has owning, operating and designing consortia. A consortium can consist of a single organization but can also be formed by several different organizations that collaborate. The system of systems itself also has the same superstructure – it has a developing consortium that determines and/or develops the standards to follow and sets the rules, an operating consortium that handles day to day operation (*e.g.,* resolving conflicts among the participants), and in principle also an initiating or owning consortium that may own physical property but perhaps more often simply facilitates the creation of the system of systems.

Fig. 2 shows this organizational structure. Note that there will likely be many CS within the SoS, each of which will have an operator, an owner and a developer. These may be shared between CS, *e.g.,* a transport SoS could contain 10 vehicles operated by two companies, where one of the companies operates 4 vehicles manufactured by Volvo while the other operates 3 Volvos and 3 BMW's.

Note that the constellations do *not* have owning, operating and developing consortia! A constellation is formed dynamically and relies on the collaboration of the constituent systems within it. There can (and, for transportation SoS will) be many constellations active at the same time. A CS can decide to leave the constellation at any time [4]. In general, there is a need for a constellation forming mediator that helps the relevant CS to find each other. There could also be mediators that help the CS in the constellation operate. In some cases, all or some of the mediators used in the SoS could be operated by the SoS operating consortium. In general, there is opportunity for market competition among the mediators – a company could, *e.g.,* develop a better constellation forming algorithm and decide to enter a SoS to try to out-compete the other constellation formation services.

What constituent systems should be included in the system of systems depends on the problem domain. What capabilities are needed in order to solve the problems for which we are designing the system of systems? The process of designing the collaborative system of systems must include two initial steps that determine first that it is not possible to create an integrated system that fulfills all needs and second that it is not possible to create a directed system of systems that fulfills the needs.

Once it has been determined that it is indeed necessary to design a collaborative system of systems, a list of desired capabilities of the constituent systems must be created. Then the cooperation of a set of owning and operating organizations whose systems can act as constituent systems of the system of systems must be gained. This requires negotiations to ensure that business models, standards and rules for the system of systems that are acceptable to all parties are in place.

The next step is to determine what mediators and infrastructure are needed. Once this has been done, the system of systems is created.

Not all constituent systems will be collaborating simultaneously, nor is a system of systems limited to solving only one problem instance at the same time. A rescue services system of systems, for instance, must be able to handle several simultaneous accidents at different locations.

The capabilities provided by the constellations are the raison d'être for the existence of the system of systems. An emergency services system of systems must be able to create constellations to handle all different types of accidents. A vehicle platooning system of systems must be able to form constellations of trucks that save fuel by driving close together. The system of systems of a country's armed forces must be able to create constellations that can solve different kinds of missions. And so on.

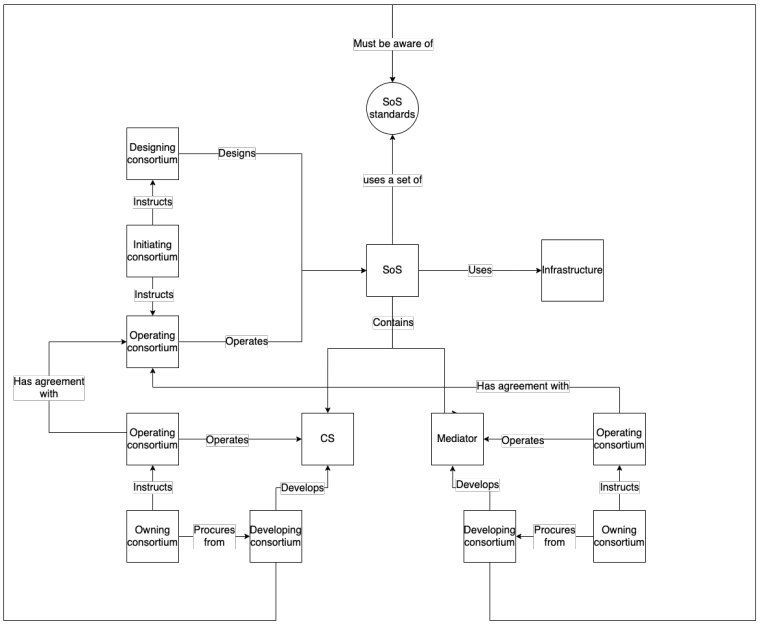

Fig. 2. Organizational structure of a system of systems. Each operating consortium must have an agreement with the SoS operating consortium, and each developing consortium must be aware of (and follow) the SoS standards. For clarity, not all relations are shown

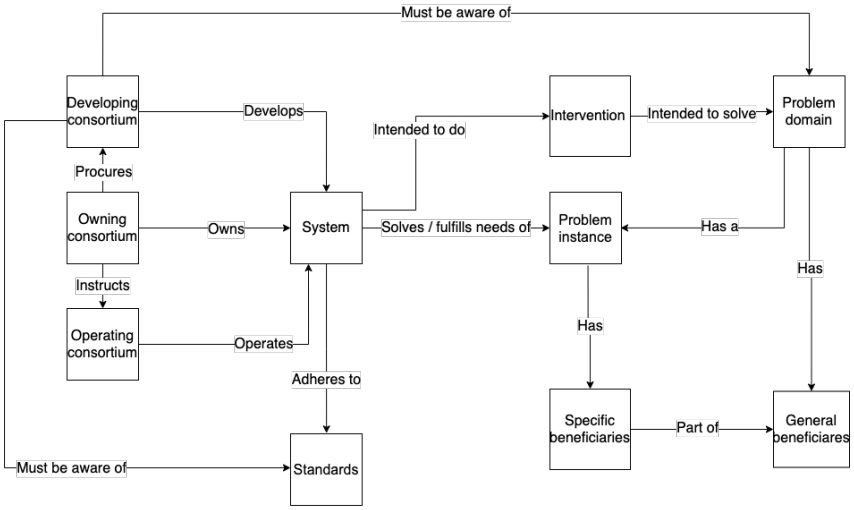

Fig. 3. The relations between a system and its intended intervention.

III. CONSTELLATIONS PERFORM INTERVENTIONS

Following Martin [5], we describe the deployment of a solution using the "Seven systems" way, meaning that the system engineering needs to take account of multiple systems in addition to the one being engineered. Martin introduces a context system, that contains a problem to be addressed; an intervention system intended to address this problem; a realization system engineers the intervention system; a deployed system that is the deployed intervention system; collaborating systems that cooperate with the deployed system; a sustainment system that provides support and maintenance to the deployed system; and finally competing systems. In addition, the context of the deployed system is often slightly changed from the original context. Fig. 3 shows parts of this. A system is intended to do interventions within a certain problem domain. The developing consortium must be aware of this domain. The deployed system solves an instance of the problem. This specific instance has a set of beneficiaries/stakeholders, which are a subset of the set of beneficiaries/stakeholders for the general problem domain. The system has owning, operating, and developing consortia, and most often must comply with some set of standards.

We will now construct the analogous illustration for a collaborative SoS.

For a collaborative system of systems, it is the active constellations that perform interventions. When designing the system of systems, we must take account of the problem domain and the generalized problem that we wish to solve. We must also ensure that the system of systems will be able to create constellations that solve the problem instances that occur. Fig. 4 shows a conceptual view of this.

Putting all of these views together, we arrive at the conceptual illustration of collaborative system of systems development shown in Fig. 5. For a specific system of systems, more complicated (larger) diagrams that specify problems, CS, mediators *et cetera* can be produced.

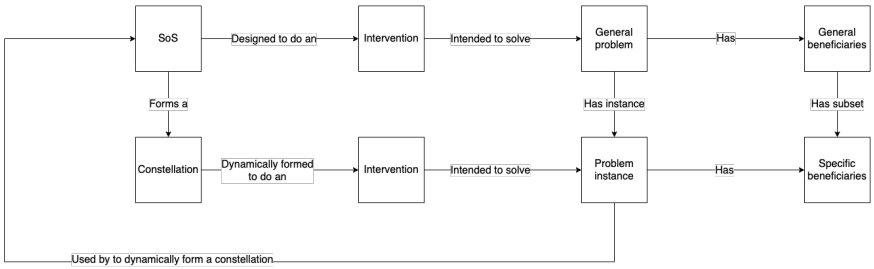

Fig. 4. A SoS is designed to do interventions within a problem domain; a constellation is dynamically formed to do an intervention that solves a problem instance.

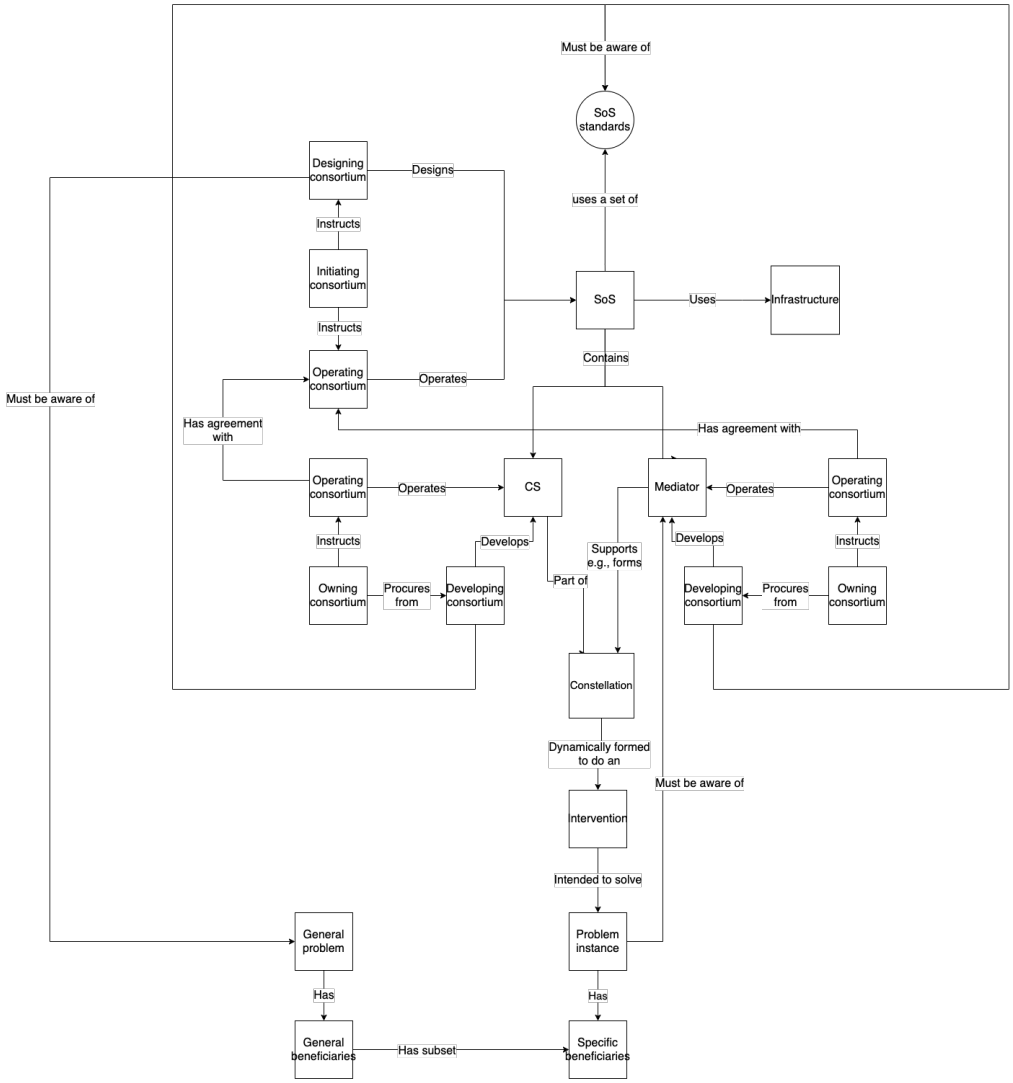

Fig. 5. View of a collaborative system of systems.

IV. A DESIGN METHOD FOR COLLABORATIVE SYSTEMS OF SYSTEMS

In the preceding, we argued that systems of systems exist to create constellations and that constellations perform interventions, *i.e.,* solve problems. This breakdown of the system of systems points to a similarly broken-down design process for collaborative systems of systems, given by the following steps:

1. Determine the problem domain. Who are the beneficiaries/stakeholders, what are the needs?
2. What is the desired value that the intervention should create? What are the values that beneficiaries/stakeholders are willing to give the intervention?
3. What capabilities are needed in order to solve the problem/execute the intervention?
    a. If the set of capabilities can be provided by a single system, build this instead of designing a system of systems.
    b. If the set of capabilities can be used to solve the problem under the direction of one party, construct a directed system of systems.
    c. Otherwise, find a set of constituent systems combinations of which can solve the problem.
4. For each constituent system from the previous step, determine what the values that it creates are. What are the values that the constituent systems (its operator and owner) would require in order to participate in the intervention?
5. Analyze the value flows thus far. Do they all fit together or are additional capabilities needed? Can these new capabilities be filled by additional constituent systems, infrastructure, or mediators? Describe the capabilities needed.
6. What value do these new elements create and what values do they need in order to participate?

The focus of the method is thus on the interventions that constellations should perform. The system of systems should be designed to facilitate the creation of such constellations.

An additional question that must be answered is who should own and operate the elements of the system of systems, and indeed who should be part of the designing consortium for the system of systems. In order to promote competition and increased efficiency, it is important that no single organization dominates the system of systems design consortium. For instance, when designing a mobility system of systems, the responsibility should not be given to an existing actor (*e.g.,* a public transport operator), so that they are avoided the temptation of building an integrated system focused on their own services.

In the next section, we apply this design method to two applications within the transport domain.

V. Applying the Method

A. Metropolitan Multi-Modal Mobility

As illustrating example, we use a mobility system of systems designed to operate in a Metropolitan setting in Sweden. The area of interest consists of a major city and its surroundings, including semi-rural areas where there is currently a perceived need for each household to own one, or more commonly more than one, cars. We are currently researching collaborative system of systems solutions for such areas.

1. The intended intervention is thus to provide transportation. The beneficiaries are travelers, with local, regional and national government as additional stakeholders. The needs are safe, secure, sustainable and flexible transportation between different areas.
2. The value that the intervention creates are safe, secure, sustainable and flexible transports. The beneficiaries are willing to pay money for this. The additional stakeholders might be willing to pay for some travels.
3. The needed capabilities involve transporting people and goods from point A to point B. To accommodate the varying needs, there is a need for autonomous vehicles of different sizes – small, medium and large. The vehicles should also be able to transport small cargo items.
4. The transport constituent systems create the value of performing a transport. They will require to get paid for this.
5. The value flows so far can be summarized in Table 1 which should be read as describing the value that the entity in a row gives to the entity in each column.

TABLE I. Value flows between different actors after step 5 of the design process for a metropolitan multi-modal mobility collaborative SoS. Values flow from the row actor to the column actor.

	User	Society	Transport operator	Intervention
User				Money for transport
Society				Subsidy for some transports
Transport operator				Performs the transport
Intervention	Flexible transportation	Transports that society subsidies have been performed		

We see from the table that the value flows don't match. There is a need for additional elements that ensure that

- The transports provided by the transport operator match the flexible transportation needs of the users.
- The money paid by the user and society is transferred to the transport operators.

There is a need for three mediators in order to fulfill these:

- A constellation formation mediator that takes the transport needs of several users and creates constellations of transport CS that can fulfill these.
- A payment distribution mediator, that ensures that each user only has to pay once and that each transport operator is paid according to its effort and agreements.
- An interface mediator that provides a simple way for users to input their transportation needs.

The design process now continues with step 6.

6. For each of these new entities, we need to determine the value they create and the value they require from the intervention in order to participate.
    a. The constellation formation mediator creates the optimized solution that solves the transport needs. It needs to collect a fee for this.
    b. The payment distribution mediator ensures that everyone gets paid. It will require a fee for this.

c. The interface mediator ensures that the users can easily input their needs. It will collect the payment from the user and take a fee.

Note that the new entities created here are roles that are needed in the system of systems. One actor could fulfill several of these roles, and it is also possible to have several different actors that take the same role. This enables competition in the system of systems. The most obvious example is that there should be several transport operators. But there are also efficiency gains to be made by having several mediators. For instance, constellation formation mediators will compete with each other based on the performance of their matching algorithms: the strive for creating more efficient constellations will lead to overall improvements of the matching process.

B. Platooning

As second example, we briefly describe the analysis of truck platooning. Platooning occurs when vehicles drive closely together in order to save fuel.

1. The problem domain is truck transportation. The beneficiaries are the truck operators themselves. Society is also a stakeholder.
2. The desired value is reduced fuel consumption. The beneficiaries are willing to pay for this, as long as the cost is less than the value of the fuel reduction.
3. The trucks/CS need to be able to drive closely together. This will require some degree of autonomous driving capability.
4. The value created by the CS are the fuel reductions. This is also the value that a CS gets out of the cooperation.
5. In order to be able to attain the fuel reductions, it is necessary for the trucks to drive closely together. To do this, they must find each other. A constellation formation mediator is needed for this. Since the size of the fuel reduction depends on the order in which the trucks drive (the leader gets a smaller reduction), there is a need for a cost distribution mediator.
6. The constellation formation mediator creates the platoons and receives a fee for this. The cost distribution mediator ensures that all participants benefit and takes a fee for this.

For this example, the results coincide with the results of an independent analysis of business models for platooning [6].

VI. Conclusions and Future Work

We presented a design method for collaborative systems of systems that enables an iterative design. We also discussed the organization of a collaborative system of systems and expressed the purpose of the system of systems as creating constellations that perform interventions in order to solve problems.

In future work, we will further refine the method and the organizational descriptions of collaborative systems of systems. We will also explore the connections between creating constellations and creating systems of systems.

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