# Adding a Detrital Actor to Increase System of System Resilience: A Case Study Test of a Biologically Inspired Design Heuristic to Guide Sociotechnical Network Evolution

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*Networking complex sociotechnical systems into larger Systems of Systems (SoS) typically results in improved performance characteristics including sustainability, efficiency, and productivity. The response, or lack thereof, of many SoS to unexpected constituent system failures undermines their effectiveness in many cases. SoS performance after faults can be improved by improving the SoS's hard (physical design) or soft (human intervention) resilience. The current approaches to increase resilience are limited due to the cost and necessary of human response increasing non-linearly with SoS scale. The limitations of current approaches require a novel design approach to improve SoS network resilience. We hypothesize that biologically inspired network design can improve SoS resilience. To illustrate this, a systems dynamics model of a Forestry Industry is presented and an optimization search over potential hard and soft resilience approaches is compared to a biologically inspired network improvement. SoS network resilience is measured through the newly developed System of System Resilience Measurement (SoSRM). Our first result provides evidence that biologically inspired network design provides an approach to increase SoS resilience beyond hard and soft resilience improvements alone. Second, this work provides evidence that having a SoS constituent fulfill the ecosystem role of detrital actor increases resilience. Third, this paper documents the first case study using the new SoSRM metric to justify a design decision. Finally, this case study provides a counter-example to the theory that increased sustainability always results in increased resilience. By comparing biologically inspired network redesign and optimized traditional resilience improvements, this paper provides evidence that biologically inspired intervention may be the needed strategy to increase sociotechnical SoS network resilience, improve SoS performance, and overcome the limitations of traditional resilience improvement approaches.*

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## 1 Introduction

Systems of systems (SoS) combine multiple complex sociotechnical systems through a network architecture to achieve additional functionality [1–5] (Fig. 1). Modern SoS combine constituent systems such as financial, utility, information, agriculture, industrial, or transportation networks. SoS design is a difficult undertaking due to the nature of SoS as complex multi-level network. Within sociotechnical systems, a population of independent agents (often people) interacts with each other, the technical artifacts in each system, and the environment [6]. As a result, sociotechnical systems are complex with many attributes that hamper design intervention. These attributes include emergence (system behavior that is not reducible to agent behavior), self-organization (including spatial-temporal agent distributions), and non-linear response to system stimuli [7–10]. Further hindering SoS design efforts, these complex sociotechnical systems (which themselves are difficult to design) are then networked together into larger SoS. One significant challenge in attempting to utilize a design methodology on SoS is that many desirable SoS characteristics (e.g., resilience, safety, sustainability, robustness) are themselves emergent that result from the interactions of the constituent complex sociotechnical systems [1,6,7,11–14].

Not surprisingly, these challenges have resulted in SoS design approaches that require significant improvement. Previous efforts in SoS design focused on overcoming the logistical and interface challenges of combining systems, but not on predicting or improving SoS operation [15,16]. As a result, engineers have successfully created SoS, but have difficulty controlling or predicting SoS dynamics [17,18]. Specifically, work is needed in improving the response of SoS to unexpected constituent system failures. Researchers recognize the importance of limiting the impact of

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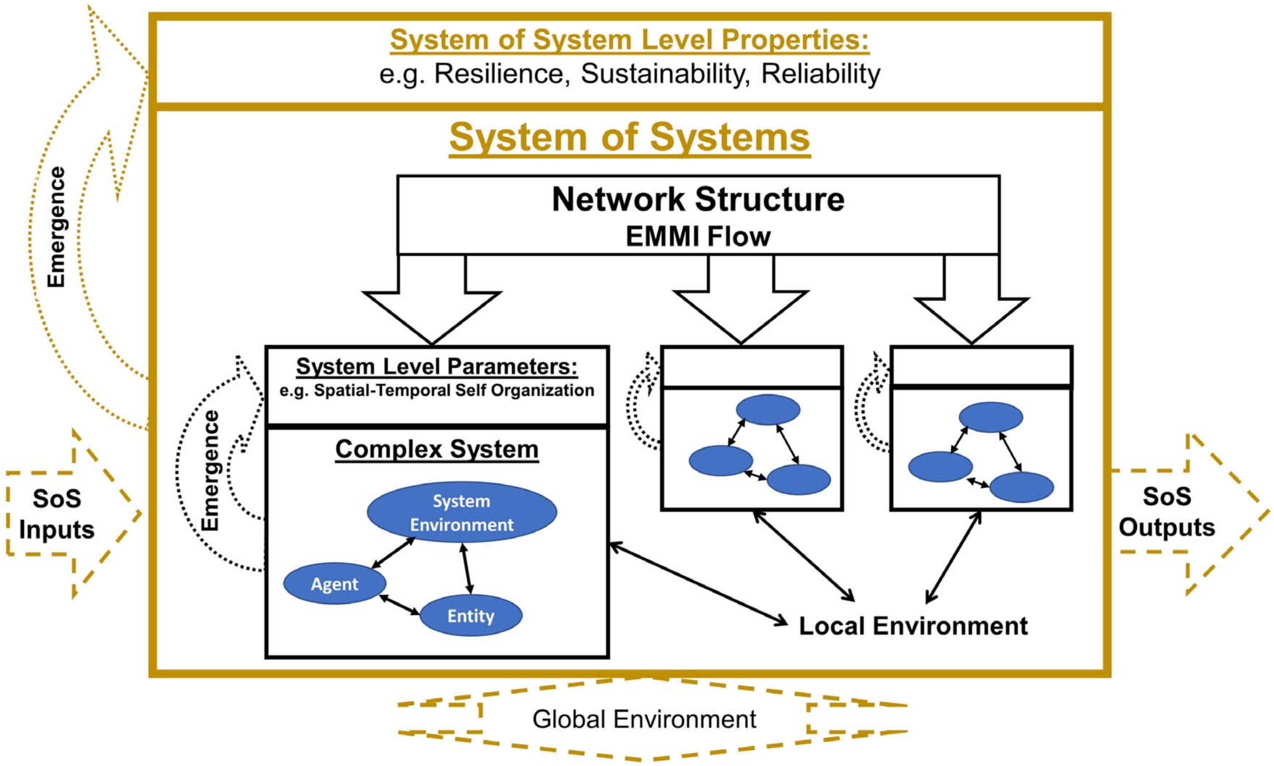


**Fig. 1 Systems of Systems as Multi-level Network of Complexity. Complex sociotechnical systems consist of mutual interactions between agents, entities (technical artifacts), and the system environment. Through emergence, their interactions result in properties measurable at the system level. These complex system properties also interact as Energy, Material, Money, and Information (EMMI) flow through their network. The combination of these interactions with the local environment results in SoS emergent characteristics (e.g., resilience). As an "open system," the SoS then undergoes another layer of interaction between itself, the global environment, and inputs to the SoS. At every hierarchical scale, complexity is present and resistant to reductionist engineering approaches.**

failures within complex systems [19], but SoS vulnerabilities still include cascading faults, difficulties in anticipating the scope of failures, and identifying critical infrastructure nodes.

Creating SoS that cannot adequately respond to local human or technical failures can have widespread impacts. On August 14, 2003, portions of the United States and Canada experienced an electrical blackout that shut down over 100 power plants and left 55 million customers without power. The cause was not a coordinated failure or widespread network attack, but a powerline in Ohio touching a tree limb [20]. Researchers estimated that the outage caused more than 90 deaths in New York City alone [21]. Unexpected failure propagation is not limited to physical SoS. On May 6, 2010, the "Flash Crash" traveled through the US stock market, causing share prices to fluctuate widely. Accenture fell to only one penny, while Apple rose to $100,000 per share. Once again, the cause was a local event tied to trades initiated in Kansas using an algorithm to sell a block of stock [22].

Emergence limits the ability of Systems of Systems Engineering (SoSE) to minimize these vulnerabilities. Emergence is a higher level observed behavior or characteristic that cannot be reduced to the behavior of subcomponents [1,3,6,8,15,23–29]. Although emergence can manifest as desirable SoS characteristics (e.g., robustness, safety, or constituent coordination), engineering methodology does not exist that can intentionally design desirable emergence into SoS [1,3,11,14]. Current Systems Engineering design tools cannot be applied to SoS, because Systems Engineering assumes systems are tightly coupled and do not exhibit Emergence [30]. Resilience, however, is an emergent SoS property that would improve SoS response to unexpected constituent faults [24].

Resilience describes the performance of a SoS after adverse events [4,31–33]. A system with high resilience would have minimal disruption and a speedy recovery to a stable state after a system fault [33]. For example, consider a power plant that experiences a turbine failure. A two-turbine plant that experiences a 50% reduction in output for 2 h is more resilient than a 1-turbine plant that experiences a 100% reduction in output for 4 h. Reducing either the duration or magnitude of the disruption increases a system's resilience. Resilience and sustainability are linked concepts [34]. A SoS might operate in an environmentally sustainable manner (i.e., zero carbon footprint), but if the SoS are not resilient, they will require additional resources to recover from faults or maintain system functionality. The material investment to recover from these faults could be so great that the lack of resilience could threaten the overall sustainability of the SoS. Given the importance of SoS in the modern world and the challenges faced by SoSE, we are interested in increasing SoS network resilience. Specifically, SoS response to faults in the network between sociotechnical systems. Thus, the central question of this research is: *What design strategies can be used to effectively increase SoS resilience?*

Some efforts to increase SoS network resilience in sociotechnical systems focus on improving human response, fault identification, or adaptation [32,35,36]. Another common approach increases resilience through adding robustness to SoS components or designing SoS with added redundancy [4,31,32]. As SoS scale, these approaches become unsustainable in their human performance and cost requirements. Perceived designer effort grows greater than linearly as network complexity grows [37].

These limitations require a novel approach to investigate SoS network resilience. Biologically inspired design may provide the needed inspiration. Non-resilient SoS by definition do not persist. Therefore, the ecosystems which currently exist are more resilient which those that suffered extinction [13]. *We hypothesize that* *biologically inspired network design can improve SoS resilience.* Biologically inspired design is a form of design by analogy that seeks to utilize existing designs in nature to improve technical artifacts [38,39]. Biologically inspired design has proven successful in the design of a wide variety of technical artifacts and in providing a framework to design adaptive engineered systems, which are artifacts with the ability to reduce the impact or recover from faults [38]. One potential application of biologically inspired design is the use of ecological network topology to inspire SoS topology. It is already known that network topography design impacts resilience [24]. For example, scale free networks have been shown to be more resilient to random node attacks, but less resilient to targeted attacks [24].

Network topography changes also are effective when applied to artifact design. Network topography optimization resulted in improved performance and superior component cooling of an electric drive train, as examined in a case study [40]. Previous research by Haley, Dong, and Tumer has shown the importance of network topography (design) on complex system performance, even suggesting that directly measuring network topography might be preferable to analysis through computationally expensive models [19]. These studies are distinct from this paper because they did not include either sociotechnical aspect to their complex systems or use biological inspiration to inform their solution.

To examine our hypothesis, we present a case study of the Kreuzung Schweizer Mittelland (KSM) Forestry Industry in the Swiss lowlands. The KSM was chosen due to containing several manufacturing constituent systems, a natural constituent system, and has performance driven by human behavior within each constituent system. We conduct an optimization search over the model parameters that investigates the potential design and human response parameters. These examined parameters mirror the current approaches of increasing resilience through improving human performance (soft resilience) and SoS physical design (hard resilience). Resilience increases due to traditional resilience improvement approaches are then compared to a biologically inspired network re-design. The network redesign adds a link inspired by the decomposer functional role found in natural ecosystems. This allows direct comparison of current approaches with biologically inspired network redesign to determine how the two compare in their attempts to increase SoS network resilience.

The research contributions of this work are as follows:

1. Evidence for our fundamental theory of sociotechnical SoS design: biologically inspired design provides a viable approach to increase SoS network resilience superior to current approaches.
2. Initial evidence that incorporating a decomposer functional role from natural ecosystems leads to an increased SoS network resilience. This contribution is derived from modeling the interaction of system architecture and resilience. Authors have stated the need to identify which "behavior topologies" result in improved performance [19]. This contribution provides an example of an improved topology to begin to fill this gap.
3. This paper presents the first case study using the new System of Systems Resilience Metric (SoSRM) metric to justify a design decision. SoSRM is a new metric used to quantify the human-centric performance measurement of resilience.
4. Evidence that increased environmental sustainability may not always lead to increased resilience. The relationship between these two measures of performance is nuanced and requires further investigation.

The paper proceeds as follows. First the background section describes current approaches to increasing resilience and the role of decomposers in ecological systems. Next, our methodology provides a brief review of the resilience metric SoSRM, a presentation of the KSM case study, and our experimental design. Finally, the results and conclusions discuss the implications and broader impacts for this SoS design approach.

## 2 Background

**2.1 Resilience.** Original investigation into the resilience of systems occurred in the fields of physics and ecology [35]. In physics, resilience is the ability of an entity to withstand a shock [35]. In ecology, resilience is an ecosystem's ability to return to a stable equilibrium point following a perturbation such as forest fires [35,41]. Unlike in physics, resilience in ecology does not require returning to the previous equilibrium point following a system fault. Therefore, any ecosystem response that does not result in extinction demonstrates resilience [41]. However, this definition from ecology neglects the dynamics of system of recovery needed in SoS [42]. As a result, engineers define resilience as the ability of a system to "absorb" and "recover" from failures [4,31,32].

Resilience engineering began as an alternate approach to risk assessment and safety engineering. Rather than focus on preventing incidents (using approaches such as Probabilistic Safety Assessment or event trees), resilience engineers recognize that system failures are non-linear phenomenon that manifest due to the complexity of sociotechnical systems [33]. Resilience engineering does not merely focus on preventing faults (e.g., improved safety procedures or interlocks), rather it also includes adaptation after faults occur (e.g., dynamic system response) [33,43,44]. Rather than focus on analyzing previous faults to prevent reoccurrence, resilience engineers seek to create models and methods to improve fault prevention and response [44]. Interestingly, early researchers realized that systems could be safe without being resilient and the opposite could also be true [24,43]. With these considerations, Hollnagel defines resilience as "the ability of a system or organization to react to and recover from disturbances at an early stage, with minimal effect on dynamic stability [33]."

Resilience is a heavily used term in research and is often interchanged with similar terms [45]. For clarity, we view resilience as distinct from either robustness or reliability. A robust SoS would not have degraded performance after a fault, but a resilient SoS may display decreased performance. Robustness allows systems to avoid degraded performance from higher frequency faults [4]. Robustness and resilience are therefore related if increased robustness aids a system in responding to a fault [46]. Resilience is also distinct from reliability. Reliability refers to the capacity of a system or system component to resist a fault [32]. While robustness enables undegraded performance after a fault, reliable components prevents faults from occurring. Reliability includes only fault prevention while resilience also includes system recovery [4].

**2.2 Current Design Approaches to Increase Resilience.** Engineering design of SoS is an research area identified with promising potential [31]. One review of design methods noted that in almost all cases, SoS are inflexible to disruptions [1]. Rather than attempt to respond to faults, engineers could attempt to design SoS with intrinsic resilience [12,47]. To understand why engineering design of SoS is an area needing additional research, it is necessary to review current approaches to increasing resilience.

There are two main approaches to increasing resilience. First, human-in-the-loop action can intervene following a fault to increase resilience [4,48]. Individuals can adapt to faults, overcoming issues not anticipated during system design [33,48]. This strategy is referred to as soft resilience [32]. Some work focuses on enabling human response to be either faster or more efficient [47]. One study examined two crisis in the historical Comtat part (current Provence-Alpes-Côte d'Azur region) of France and demonstrated that resilience can be improved when individuals recognize and respond more rapidly to the fault [35]. Other work focuses on what type of recovery strategy will most quickly restore SoS performance after a disaster [49]. This can be accomplished by guaranteeing that there are sufficient assets or workers available to respond after a fault occurs [4]. Computer modeling is one approach to test and improve recovery approaches [7,23,49–51]. Agent-based modeling has proved to be especially valuable in these efforts. A final strategy called "drift correction" involves implementing repair or recovery approaches prior to full fault occurrence [4].

Attempting to implement soft resilience, however, faces significant challenges. Most obviously, individuals sometimes make mistakes [52]. The use of human-in-the-loop is limited by the individual's cognitive processing of the SoS [33,35]. SoS may display non-linear or multi-scale dynamics [53]. Additionally, humans must be able to make and implement response strategies faster than the problem and environment are evolving [35,44,53]. Decision makers must also have accurate current information (analogous to the need for accurate sensors with low noise in control systems). In organizations with centralized decision making (directed SoS), the difference between manager perception and operator reality compromises human-in-the-loop intervention [54]. Lastly, given the complexity of SoS, it is non-trivial to ensure human intervention does not result in unintended consequences more severe than the original fault [33,35,41,46].

Given the limitations of implementing soft resilience, a second strategy focuses on the physical engineering of the SoS. This method is referred to as hard resilience [32]. Hard resilience includes strategies including engineering the SoS network or constituent design decisions which seek to improve the performance of their constituent system. Engineers seek to identify vulnerable areas and implement engineering solutions to increase resilience [2,31,55]. This can consist of increasing the robustness of the system to ensure faults never lead to degraded performance [31,55]. For example, in a power distribution system this could include adding redundant power supplies or hardening cables [32]. Designing a SoS with excess capacity may also improve hard resilience. When a fault occurs, the remaining capacity could still be sufficient for SoS performance [56]. This excess capacity provides physical or function redundancy [4]. Another strategy is investing in resources to speed SoS recovery after a fault occurs [4,57]. Finally, some design guidelines promote building SoS to maximize the ability of constituents to communicate. Authors propose that this will aid in recovery coordination [4], but it is also possible that increasing a SoS network density could promote fault propagation.

The current strategies to increase hard resilience in SoS have limitations and offer unique challenges. First, to harden a system against a fault requires the potential fault to be identified [32,56,58]. Although current literature provides methods to identify areas vulnerable to faults [2], the identification of all faults may be impossible for various reasons [7,12,31,46,59]. The potential faults may be masked due to limitations in the engineer's modeling of the system, changing SoS environment, or changing system boundary [4,45,60]. Varying environmental or operator characteristics allows for the possibility of new faults that were not originally anticipated during SoS implementation [33,45,56,60,61]. Compounding this, the set of all possible faults increases non-linearly as the complexity of SoS grows. It is not possible to prevent all faults [4,32] even if all the faults can be identified. Further, combining resilient SoS components could produce emergence in a way that results in an unresilient SoS [62]. The inability to anticipate all possible SoS faults can cause hardening and redundancy implementation that results in excess resilience in one portion of a SoS and inadequate resilience in other portions [4,63]. System hardening also can be quite expensive [4,7,32,50]. Thus, hardening strategies are often considered as an inefficient method to increase resilience [4,7,46,63].

Further, hard resilience strategies that focus on ensuring recovery occurs quickly may be inadequate because once a fault occurs even a rapid recovery could have unacceptable long-term repercussions [4,61]. For example, the 2003 electrical blackout only lasted for 2 days in New York City, but researchers estimated that the outage caused more than 90 additional deaths in New York City alone [21]. Some very brief faults can even result in deadlocked scenarios, eliminating possible recovery [61]. The Chernobyl disaster provides an example of this. Speeding recovery is effective to increase resilience for time-bounded scenarios, however, where recovery must occur within a given window for the SoS to remain viable [61].

As a result of the challenges in implementing hard and soft resilience, SoS are often highly resilient to a small, specific set of faults, often those that have already occurred [4,60,63]. The statistical probability of SoS fault frequency can follow a fat-tailed distribution, which makes it impractical to only focus on frequent or anticipated faults. Researchers describe the high likelihood of disruptive events in SoS in terms ranging from "greater than in a system" to "inevitable" [44,55,62]. Finally, constituent hardening or design could result in unintended SoS consequences (e.g., when a constituent system upgrade causes negative SoS performance) [11,62].

The limitations in implementing hard and soft resilience indicate a new approach may be required. Unlike technical artifacts, SoS are not designed completely during an initial design stage [1–3,64]. Rather SoS continually evolve as new systems are added to existing legacy systems [1,65]. For example, a SoS could add an additional electrical supply source to a factory. The SoS network topography is susceptible to design intervention during these critical evolution decision points. SoS network evolution occurs at distinct points in time as multiple stakeholders agree to combine their constituent systems. Decision makers considering multiple possible SoS network topography changes would benefit from an approach to indicate which option would result in increased resilience. For example, would it be more resilient to add an additional power supply to a network (add a network node) or add redundant pathways between the existing power supplies and loads (change network link structure)?

This problem structure indicates that SoS network design heuristics may be a powerful approach to increase SoS performance. Utilizing heuristics allows non-case study specific guidance to be given; heuristics provide designers with a principle-based approach to problem solving [38,66]. The most valuable heuristics are reliable, are used frequently (SoS undergo periodic evolution), and require frequent revision (we do not anticipate network level guidance to require revision) [66]. Authors theorize that process-focused heuristics (e.g., network evolution guidance) might be more broadly applicable than the type of artifact-focused heuristics currently in use today by teams such as the Jet Propulsion Laboratory's A-team [66].

Biologically inspired design is one field of study that could be used to create design heuristics for SoS [67]. For example, one previous study utilized blood vessel fractal geometry as inspiration for organizing air traffic patterns, successfully simplifying numerical optimization calculation complexity [68]. Ecosystem modeling of network characteristics when translated to engineered systems could result in increased resilience [69]. This work provides a first step by investigating a heuristic to increase SoS network resilience: Seek to ensure the SoS has a constituent system which fulfills the decomposer functional role (detrital actor).

### 2.3 Biological Inspiration: The Decomposer Functional Role.

Biological species take one of multiple functional roles defined by their part in the material and energy flow through an ecosystem (Fig. 2). These include producers, consumers, and decomposers [70]. Primary producers (e.g., plants), use solar energy and nutrients to produce plant biomass. A consumer then consumes this biomass directly (i.e., herbivores) or indirectly (i.e., carnivores or omnivores) through the consumption of another organism. Decomposing organisms feed on dead or waste organic matter from ecosystems, or detritus, to keep material and energy in the system by making them available to primary producers and consumers [71]. The decomposer functional role (e.g., detrital actors), consisting of decomposers (e.g., fungi) and detrital feeders (e.g., earthworms, slugs, millipedes, etc.), is vital to natural ecosystems by promoting material and energy recycling [71]. These members of the decomposer functional role, or detrital actors, are the keys to the magnitude of cyclic flows within an

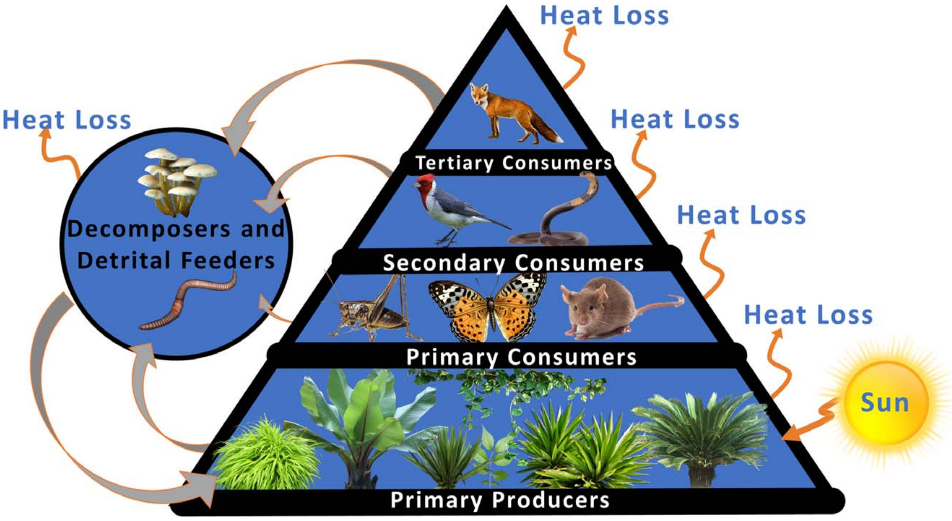


Fig. 2 Ecosystem functional roles and dynamics

ecosystem and facilitate the transformation of a food chain into a more cyclic production system [71].

Ecologists have shown that the inclusion of the detrital actors into ecosystems makes available some fraction of the embedded energy that would otherwise not be utilized, which impacts the biodiversity, food web structure, and transient responses of ecosystems [71]. Detrital actors support ecosystem diversity, which ecologists theorize in turn promotes ecosystem stability [72]. Some studies have shown that detrital actors can be involved with over half of the material flows within an ecosystem [72,73]. Detrital actors provide the critical function of breaking down larger organic matter to increase the detritus surface area. Detritus breakdown enables more efficient energy flow to higher trophic levels in an ecosystem [74]. Additionally, detrital actors may incorporate nutrients at a different time scale than higher trophic level actors, providing another impact of detrital actors to ecosystem dynamics [71].

### 2.4 Translating the Decomposer Functional Role to SoS Design.

The translation of functional roles, structural connectivity, and flow-based configurations found within natural ecosystems into engineered system components is accomplished by identifying and mapping basic functions that exist within both industry and nature. These include the consumption of energy and materials, transforming materials and energy into products, and breaking down products to make them re-available [75]. Using this approach to describe and model SoS show strong disparities when compared to ecosystems. For instance, the characteristics of SoS show a limited number of primary consumers (herbivores in natural ecosystems) and abundance of dependent consumers (carnivores in natural ecosystems). Furthermore, the decomposer functional role found in natural systems is often minimal or absent [74], which reduces material cycling within the SoS [72]. This material cycling deficiency has resulted in dependence on virgin resources, supply chain vulnerability, and contributes to the global environmental crisis through excess waste generation [72].

Previous work has investigated the role of incorporating detrital actors into SoS, but not from a resilience perspective. One study proposed utilizing the wetlands near an industrial park as an ecosystem service to fulfill the role of detrital actor [74]. Although this approach was shown to successfully increase the sustainability (i.e., energy and water recycling) of steel production within the industrial park, the impacts on resilience were not examined by the authors [74]. Previous studies also have determined that adding detrital actors to man-made systems could enable man-made systems to mimic ecosystem robustness [72]. That work, however, focused on improving a cycling structural metric derived from graph theory, but did not investigate the role increased cyclicity had on SoS resilience.

## 3 Methodology

### 3.1 Measuring Resilience: SoSRM.

The natural systems that have high resilience must be identified before their characteristics can be used to inform SoS design. In a previous work, we proposed SoSRM to reflect the unique needs of SoS resilience measurements [76]. This metric was designed to recognize that the important leverage points within a SoS is at the constituent system interfaces [4,15,61]. SoSRM uses a standardized fault and recovery duration across various SoS architectures. SoSRM measurement captures SoS dynamics such as cascading faults, delayed feedback loops, and network interdependencies. Finally, SoSRM is applicable to both Ecosystems and Man-made SoS, which allows works such as this paper that explores the biologically inspired design of SoS. SoSRM methodology uses SoS characteristics to identify fault locations and elements of graph theory to define fault and recovery duration.

The SoSRM is calculated as follows:

$$SoSRM = \frac{1}{k}\sum_{fault=1}^{k}\frac{\int_{t_o}^{t_o+T^*}\left[\frac{1}{n}\sum_{g=1}^{n}Q_g(t)\right]dt}{T^* * \frac{1}{n}\sum_{g=1}^{n}Q_g(0)} \tag{1}$$

where $n$ is the total number of subsystems within the SoS, $k$ is the number of SoS links in the SoS, $Q_g(t)$ is a constituent's measure of performance (MOP) at time $t$, $Q_g(0)$ is a constituents system steady-state measure of performance prior to fault occurrence, $t_o$ is the time when a constituent fault occurs, and $T^*$ is a "suitably long interval" to determine lost functionality. SoSRM fault duration allows 62.3% of the energy to flow through the system ($T^T$). 63.2% is the expected percentage change in a first-order system following a transient during one time constant as defined in control engineering. After the fault is inserted, SoSRM incorporates SoS response for an additional $T^T$. This allows SoSRM results to incorporate how quickly the SoS recovers from each fault.

SoSRM values are typically between 0 and 1. A SoSRM greater than 1 indicates that expected SoS performance would improve if a link was broken. A way to consider SoSRM values is to consider a SoS where the combined MOPs for all systems is one million dollars per year equivalent, $T^T$ is 6 months, and SoSRM is 0.922. This means that the expected MOP loss when a SoS link is broken is $78,000 equivalent. Conversely, the expected MOP loss

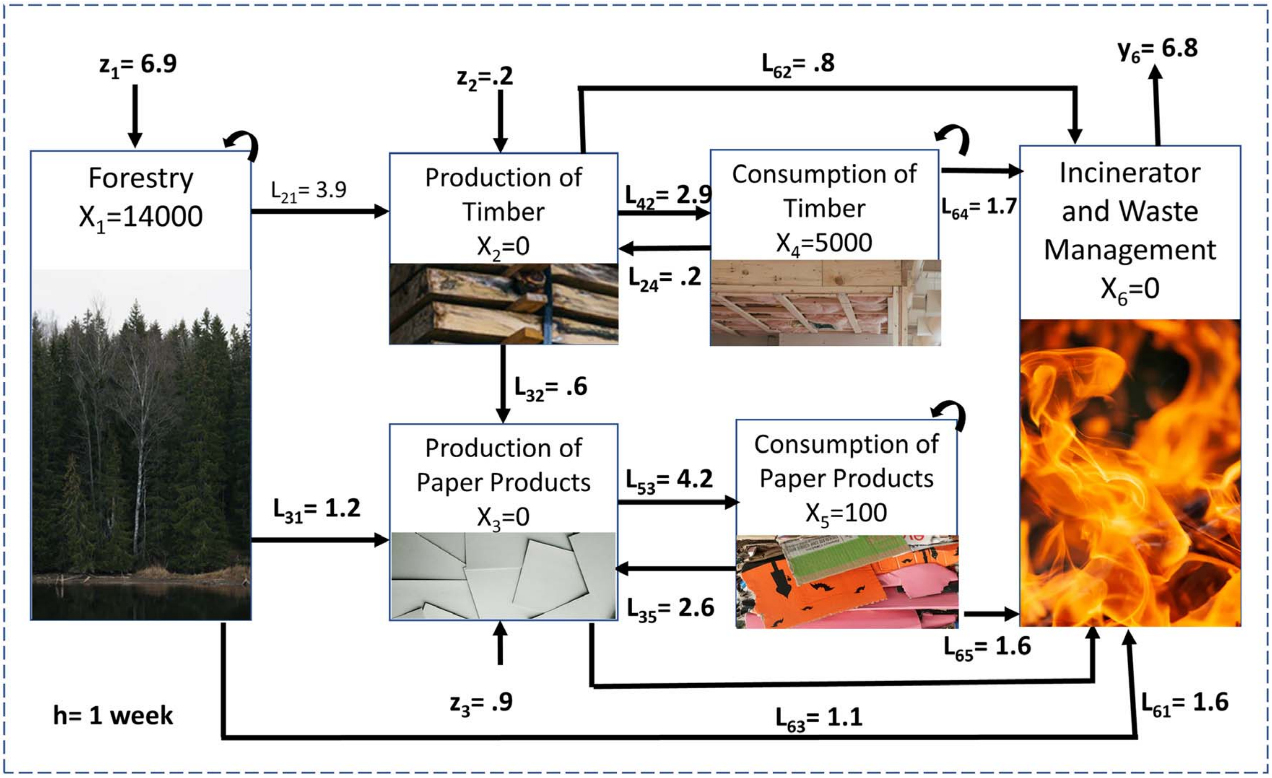


**Fig. 3 Status-Quo KSM Forestry Region SoS. Adapted from Ref. [77].**

for a SoSRM of 0.6 is $400,000 equivalent. These expected losses are annotated Expected Financial Losses due to SoS Link Failure (*E[$SoSRM]*). SoS are large scale systems which often have combined MOPs much greater than 1 million dollars equivalent per year. Thus, even small changes in SoSRM could lead to substantial financial savings. For additional information on SoSRM, see Ref. [76].

**3.2 Case Study: Kreuzung Schweizer Mittlelland Forestry Region.** The case study examined was of the forestry industry in (KSM, Switzerland. The original model was built on data collected in a study whose goal was to ensure the KSM continued to be self-sufficient [77]. This case study consists of 12 SoS Links and six systems. Flows shown in Fig. 3 are in kilograms dry matter per capita per week. Stocks are recorded in kilograms dry matter per capita. This SoS has three input flows: $Z_1$: forestry growth, $Z_2$: lumber imports, and $Z_3$: pulp paper imports.

KSM was selected because its sociotechnical architecture reflects both conservation of mass flow between the constituents and the interaction of the human choices. This interaction of human choices is defined in some works as a behavioral network [19]. Previous research has considered either conservation based flows (without behavioral interactions) or behavioral interactions within an artifact (without conservation based flows) [19,40]. Although the links in Fig. 3 represent physical connections between the constituent systems, the material flows also impact constituent decisions. Thus, this case study also incorporates the effects of the KSM "behavior networks" an aspect of SoS that was identified as crucial in previous efforts to explore topography changes to system performance [19]. This paper expands upon Refs. [19,40] because these case studies were technical artifacts (i.e., drivetrains and cooling systems), not sociotechnical systems.

Table 1 KSM model parameters and optimization search space

| Parameter | Model value | Optimization search | | System | Resilience type |
|---|---|---|---|---|---|
| | | Min | Max | | |
| FLAG | 1 week | 0 | 52 | $X_1$ | Soft |
| FTPP | .1 | .1 | 1 | $X_2$ | Soft |
| FPPP | .1 | .1 | 1 | $X_3$ | Soft |
| X6nopenalty | .2 | 0 | 5 | $X_6$ | Hard |
| X6maxstorage | 1 | 0 | 5 | $X_6$ | Hard |
| TRR | 0.105 | 0 | 1 | $X_2X_4$ | Hard |
| PRR | 0.62 | 0 | 1 | $X_3X_5$ | Hard |
| ForestMin | 14,000 | 0 | 14,000 | $X_1$ | Hard |

Of note, KSM is not at steady-state. The stocks in systems $X_1$ and $X_5$ increase at a rate of 0.2 kg per capita (0.1%) and 1.0 kg per capita (1%), respectively. Second, only systems $X_1$, $X_4$, and $X_5$ are designed to have a stock. $X_2$, $X_3$, and $X_6$ are designed to have no standing stock (i.e., a mean residence time of zero). These three constituents ($X_2$, $X_3$, and $X_6$) have a direct input/output process. Of course, the processes in these three constituent systems ($X_2$, $X_3$, and $X_6$) take time, but for KSM model formulation, we assume stock accumulation during conversion to be negligible compared to the model time-step of $h = 1$ week. Time step ($h$) is chosen to be short enough to ensure that model responses accurately reflect system dynamics, short enough to ensure the sum of the rows of the one-step transition matrix are less than one (a step in calculating $T^T$ [76]), and long enough to minimize computational expense.

When estimating the value of SoSRM in dollars, the following assumptions were utilized to provide a rough estimate. KSM gross domestic product for the constituent systems is not available, but the Swiss Central Plain (where KSM is located) 2012 lumber profits was approximately $204,249.94 [78]. To provide a conservative estimate, we will assume that $X_1$'s MOP ($204,249.94/year) is the value of the MOP of the entire KSM used to calculate E[$SoSRM]. Of course, $X_{2\text{-}6}$ MOPs have financial value as well, but as an extremely conservative estimate of the financial value of the resilience improvement approaches in this paper, they will be omitted.

**3.3 Case Study: System Dynamic Model Formulation.** The first key modeling decision is defining the MOP for each constituent system. In ecological systems, SoSRM calculations have been conducted with MOPs defined as standing Biomass [76]. This approach is not a realistic option for man-made SoS for two reasons. Some of the systems are designed to have no standing stock ($X_2$, $X_3$, $X_6$), and standing stock is not a reasonable approximation for constituent success. As shown in Eq. (1), MOP definition plays a critical role in SoSRM calculation. MOPs must be carefully defined to avoid distorting simulation results. MOP formulation assumed that constituents desired to maximize their own utility and would always act in their own self-interest. Utility was defined based on the characteristics of each constituent system. Utilities considered were profit, sustainability, and services provided. Not all constituents considered all possible measures of utility (reflecting competing goals in socio-technical systems). Although the overall goal of KSM is self-sufficiency, most constituents do not consider sustainability in their MOP. For example, the Forestry system ($X_1$) attempts to maximize profit without engaging in unstainable activities while Consumption of Timber ($X_4$) MOP is driven by ensuring sufficient processed lumber was available within KSM. This provides a model that reflects the disparity in real-world motivations and does not require a utopic SoS where every constituent desires sustainability for sustainable SoS behavior to still be a goal. Appendix A presents our specific MOP definitions and justifications.

Additionally, the differential equations for KSM must incorporate the actions of the intelligent agents (people) that control each constituent systems. Intelligent agents can make choices to respond to SoS link failures, such as increasing Forestry ($X_1$) production (e.g., $L_{21}$) when a recycling link (e.g., $L_{24}$) is lost. Each constituent system will act to maximize their MOP as defined in Appendix A. The KSM differential equations are presented in Appendix B. Examination of the equations in Appendix B reveal that SoS response depends on model parameters that impact both soft and hard resilience. These parameters are summarized in Table 1.

Human response following a constituent fault impacts the soft resilience of a SoS. Human response was incorporated into the model three ways. First, Forestry ($X_1$) responds to supply shortcomings downstream by increasing timber production. However, this response from the Forestry ($X_1$) is subject to a delay time (the variable FLAG) as the additional lumber harvesting resources activate of 1 week. The Production of Paper and Lumber systems ($X_2$ and $X_3$) seeks to maintain zero standing stocks. A simple proportional controller throttles the incoming flows from the Forestry Industry with a proportional constant of 0.1. The higher the proportional constant (FTPP and FPPP), the more responsive is $X_2$ and $X_3$.

Constituent design decisions impact the hard resilience of the SoS. These design parameters were implemented into the model in the following ways. First, the Incinerator ($X_6$) has two design parameters that impact resilience. The Incinerator ($X_6$) MOP is driven by the constituent system's desire to maintain standing stock at zero (efficiently incinerate all incoming waste). There is an amount of waste the Incinerator ($X_6$) can store without incurring a financial penalty ($X_6$nopenalty). Additionally, there is an amount of storage where the Incinerator ($X_6$) has so much stored waste that the cost of storage outweighs the profits made as a waste disposal company ($X_6$maxstorage). The recycling rate implemented by $X_4$ and $X_5$ of timber and paper (Timber Recycle Rate (TRR) and Paper Recycle Rate (PRR)) also impact SoS resilience. Finally, the Forestry System ($X_1$) has a minimum level; it will allow the standing stock of trees to reach (ForestMin). This could be highly conservation motivated where the standing stock in Forestry ($X_1$) is not allowed below the initial level of 14,000 kg per Capita. Conversely, the SoS could have no conservation consideration and allow Forestry ($X_1$) level to reach zero kilograms per Capita. While the first scenario would never allow logging below initial Forestry ($X_1$) population, the second approach would allow for complete deforestation in response to a SoS fault. Model parameter settings during SoSRM evaluation are per Table 1.

Verification of the modeling included line-by-line code checks and exercising the KSM model over a variety of initial conditions and faults to ensure system performance matched anticipated response. All optimal results were re-simulated and closely monitored to ensure no unexpected model artifacts drove design solutions. The model was executed within Anylogic 8.4 University Edition. Model unit time was weeks. Simulation runs were conducted on a personal laptop with an Intel® Core™ i5-7000U CPU operating at 2.50 GHz and 16.0 GB of RAM.

**3.4 Optimizing Status-Quo Resilience Improvements.** An optimization search of the KSM model evaluated the possible resilience improvement by utilizing the traditional approaches of improving soft and hard resilience. Two independent searches were conducted. The first objective function was to maximize SoSRM, while the second objective function was to minimize SoSRM. These independent searches provided two insights. First, they revealed if SoSRM was bounded despite resilience improvement efforts. Second, the maximization search resulted in the highest SoSRM achievable by traditional resilience improvement approaches. Table 1 lists the model's parameter range search space. The search evaluated 500 samples. These results provide a benchmark to compare traditional approaches to improve resilience against biologically inspired network design.

The built-in Optimization Experiment within Anylogic was used to conduct the optimization searches. Anylogic utilizes the OptQuest optimization engine, a proprietary population-based metaheuristic search engine [79]. OptQuest utilizes methods such as scatter search, evolutionary approaches aided by a multivariate linear regression module, neural network to identify new trials, satisfiability data mining approach, and Markov Blankets [80].

**3.5 Biologically Inspired Network Improvement.** Contrasting traditional resilience improvement approaches, we next implemented a biologically inspired network change. Within SoS, network topography changes often occur slowly and require constituent coordination, making them susceptible to design heuristic intervention. The heuristic tested in this paper is: *Ensure the SoS has a constituent system that fulfills the decomposer functional role (detrital actor) found in natural ecosystems*. Following this heuristic, we added a link from the Incinerator ($X_6$) to the Forestry ($X_1$) constituent system (Fig. 4). Of course, adding a network link is also potentially a form of adding hard resilience to the SoS.

In the original configuration, the Incinerator ($X_6$) took the role of apex predator. All other systems sent flows to $X_6$. No constituent system, however, fulfilled the decomposer functional role. This deficit is unsurprising as man-made systems often do not incorporate detrital actors [74].

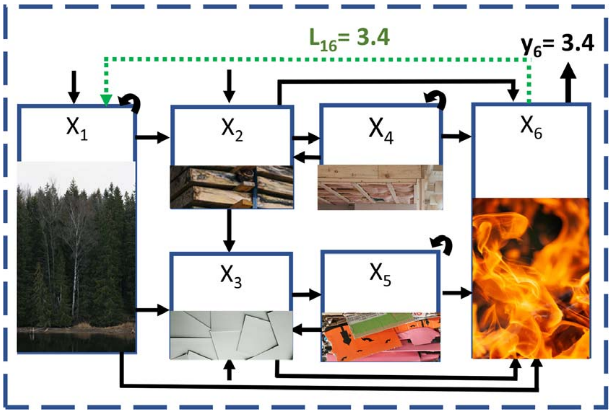


Fig. 4 Biologically Inspired Modification of KSM Forestry SoS

**Table 2 KSM SoSRM results summary**

| Parameter | Status-quo | Bio-inspired redesign | Status quo optimization Min | Status quo optimization Max | Bio-inspired optimization Min | Bio-inspired optimization Max |
|---|---|---|---|---|---|---|
| **SoSRM** | **0.909** | **0.926** | **0.764** | **0.922** | **0.743** | **0.931** |
| Best TRIAL | – | – | 384 | 363 | 467 | 434 |
| <2% from Best | – | – | 2 | 30 | 47 | 30 |
| FLAG | 1 | 1 | 51.9 | 0 | 52 | 0 |
| FTPP | 0.1 | 0.1 | 1 | 0.1 | 1 | 0.1 |
| FPPP | 0.1 | 0.1 | 0.88 | 0.1 | 1 | 0.1 |
| X6nopenalty | 0.2 | 0.2 | 0.22 | 5 | 1.257 | 5 |
| X6maxstorage | 1 | 1 | 1 | 5 | 1.007 | 5 |
| TRR | 0.105 | 0.105 | 0.9 | 0 | 0.899 | 0 |
| PRR | 0.62 | 0.62 | 0.01 | 0.807 | 0.003 | 0.803 |
| ForestMin | 14,000 | 14,000 | 13,995 | 592.3 | 3254 | 0 |

As shown in Fig. 4, $L_{16}$ supplements the original SoS by connecting $X_6$ to $X_1$. This link simulates adding a mulching approach to the KSM waste stream, which returns nutrients and energy to the SoS similar to the decomposer role in natural systems. Mulching improves tree seedling survival, tree growth, soil moisture retention, and tree size in forests [81]. For this SoS, we assume that half of the received waste is eligible for mulching, and the remainder disposed by incineration. The only additional impact of $L_{16}$ to the SoS constituent dynamics is that the flow of $L_{16}$ caused $X_1$ stock to increase more rapidly. $X_1$ stock increases at a rate of 3.6 kg/capita per week rather than 0.2 kg/capita per week as in the unmodified SoS.

The effectiveness of this biologically inspired network rearrangement was tested by both measuring SoSRM as well as conducting an optimization search per Table 1 to determine the maximum and minimum achievable SoSRM for the biologically inspired KSM. The optimization search provides the maximum possible SoSRM when combining traditional approaches with biologically inspired network re-design.

## 4 Results and Discussion

Using the biologically inspired design heuristic resulted in an improved SoSRM over traditional hard and soft resilience improvements. These results are summarized in Table 2. The Best Trial row reports which search iteration resulted in the optimal result, while the <2% from best row records when the search results were within 2% of the optimal result. The <2% value provides an indication of how quickly the search converged to the optimal value.

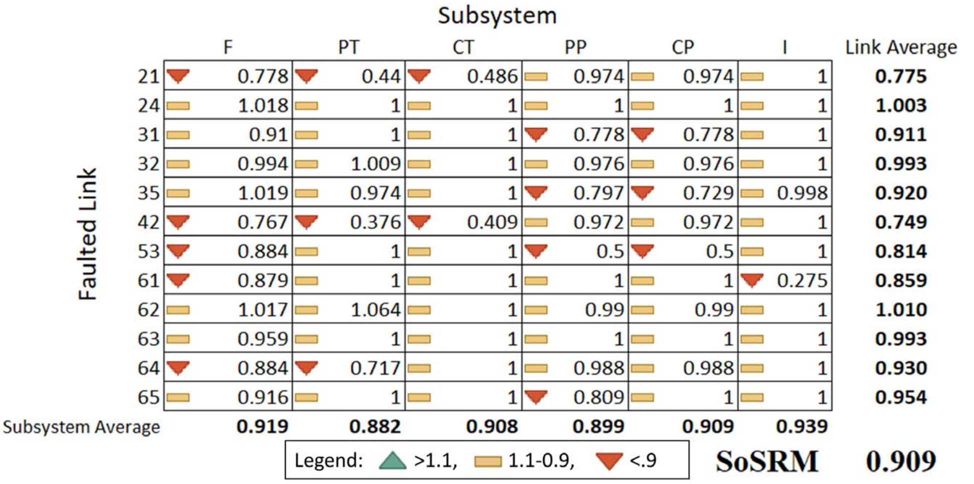
### 4.1 Kreuzung Schweizer Mittlelland Status-Quo SoSRM.

SoSRM calculation for KSM Status-Quo is shown in Table 3. Of note, the KSM SoS is quite resilient initially, with a SoSRM of 0.909 (E[\$SoSRM] approximately 2 million dollars). One reason is that the SoS inherently has a large amount of hard resilience in the form of unused reserve capacity in the Forestry ($X_1$) and Incinerator ($X_6$) constituent systems. If inflows for the Forestry ($X_1$) system were to cease, it would take 43.4 years for complete deforestation to occur. Similarly, it would take 50.6 years for Timber Consumption ($X_4$) to be depleted to zero standing stocks. The reserve capacity designed into the KSM also resulted in large values for $T^*$ and $T^T$. $T^*$ was 111.8 years and $T^T$ was 55.9 years. These values show that the KSM is relatively insensitive to short duration faults.

### 4.2 Kreuzung Schweizer Mittlelland Traditional Resilience Improvements.

Traditional methods successfully increased SoSRM from .909 to .922. This results in an improved E[\$SoSRM] savings of approximately \$300,000. The specific parameter results provide some interesting insights into the KSM SoS. First, the TRR that results in the highest SoSRM was 0 (i.e., no recycling from Consumption of Timber to Production of Timber). This counter-intuitive result may be explained by a closer examination of the SoS response when $L_{24}$ is broken in Table 3. This is one of the two scenarios in Table 3 when the overall performance of the SoS improves due to a broken link. SoS performance improves because the 0.2 inflow to $X_2$ from $L_{24}$ is replaced by increasing $L_{21}$ by 0.2. This 0.2 is the flow that

**Table 3 KSM status-quo SoSRM calculation**

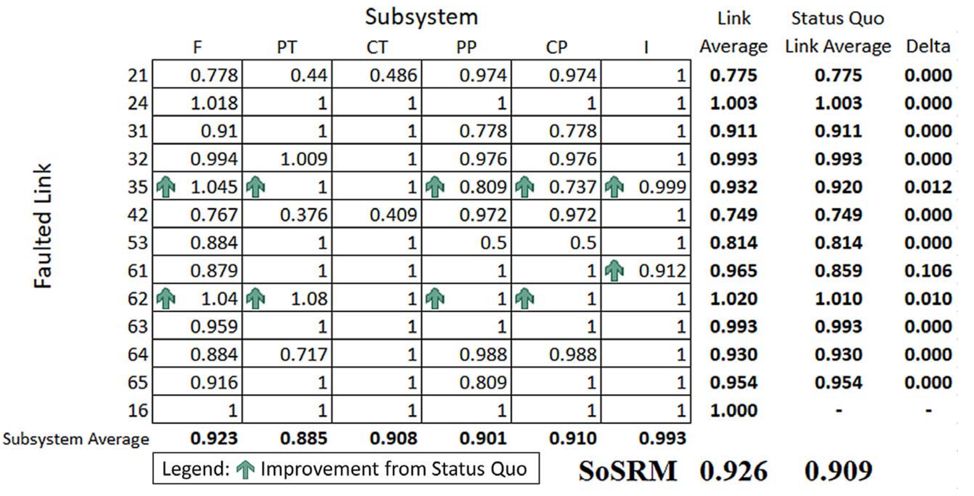


| Faulted Link | F | PT | CT | PP | CP | I | Link Average |
|---|---|---|---|---|---|---|---|
| 21 | ▼ 0.778 | ▼ 0.44 | ▼ 0.486 | ▬ 0.974 | ▬ 0.974 | ▬ 1 | **0.775** |
| 24 | ▬ 1.018 | ▬ 1 | ▬ 1 | ▬ 1 | ▬ 1 | ▬ 1 | **1.003** |
| 31 | ▬ 0.91 | ▬ 1 | ▬ 1 | ▼ 0.778 | ▼ 0.778 | ▬ 1 | **0.911** |
| 32 | ▬ 0.994 | ▬ 1.009 | ▬ 1 | ▬ 0.976 | ▬ 0.976 | ▬ 1 | **0.993** |
| 35 | ▬ 1.019 | ▬ 0.974 | ▬ 1 | ▼ 0.797 | ▼ 0.729 | ▬ 0.998 | **0.920** |
| 42 | ▼ 0.767 | ▼ 0.376 | ▼ 0.409 | ▬ 0.972 | ▬ 0.972 | ▬ 1 | **0.749** |
| 53 | ▼ 0.884 | ▬ 1 | ▬ 1 | ▼ 0.5 | ▼ 0.5 | ▬ 1 | **0.814** |
| 61 | ▼ 0.879 | ▬ 1 | ▬ 1 | ▬ 1 | ▬ 1 | ▼ 0.275 | **0.859** |
| 62 | ▬ 1.017 | ▬ 1.064 | ▬ 1 | ▬ 0.99 | ▬ 0.99 | ▬ 1 | **1.010** |
| 63 | ▬ 0.959 | ▬ 1 | ▬ 1 | ▬ 1 | ▬ 1 | ▬ 1 | **0.993** |
| 64 | ▼ 0.884 | ▼ 0.717 | ▬ 1 | ▬ 0.988 | ▬ 0.988 | ▬ 1 | **0.930** |
| 65 | ▬ 0.916 | ▬ 1 | ▬ 1 | ▼ 0.809 | ▬ 1 | ▬ 1 | **0.954** |
| Subsystem Average | **0.919** | **0.882** | **0.908** | **0.899** | **0.909** | **0.939** | |

Legend: ▲ >1.1, ▬ 1.1-0.9, ▼ <.9

**SoSRM 0.909**

**Table 4 KSM biologically inspired design SoSRM calculation**



| Faulted Link | F | PT | CT | PP | CP | I | Link Average | Status Quo Link Average | Delta |
|---|---|---|---|---|---|---|---|---|---|
| 21 | 0.778 | 0.44 | 0.486 | 0.974 | 0.974 | 1 | **0.775** | **0.775** | **0.000** |
| 24 | 1.018 | 1 | 1 | 1 | 1 | 1 | **1.003** | **1.003** | **0.000** |
| 31 | 0.91 | 1 | 1 | 0.778 | 0.778 | 1 | **0.911** | **0.911** | **0.000** |
| 32 | 0.994 | 1.009 | 1 | 0.976 | 0.976 | 1 | **0.993** | **0.993** | **0.000** |
| 35 | ↑ 1.045 | ↑ 1 | 1 | ↑ 0.809 | ↑ 0.737 | ↑ 0.999 | **0.932** | **0.920** | **0.012** |
| 42 | 0.767 | 0.376 | 0.409 | 0.972 | 0.972 | 1 | **0.749** | **0.749** | **0.000** |
| 53 | 0.884 | 1 | 1 | 0.5 | 0.5 | 1 | **0.814** | **0.814** | **0.000** |
| 61 | 0.879 | 1 | 1 | 1 | 1 | ↑ 0.912 | **0.965** | **0.859** | **0.106** |
| 62 | ↑ 1.04 | ↑ 1.08 | 1 | ↑ 1 | ↑ 1 | 1 | **1.020** | **1.010** | **0.010** |
| 63 | 0.959 | 1 | 1 | 1 | 1 | 1 | **0.993** | **0.993** | **0.000** |
| 64 | 0.884 | 0.717 | 1 | 0.988 | 0.988 | 1 | **0.930** | **0.930** | **0.000** |
| 65 | 0.916 | 1 | 1 | 0.809 | 1 | 1 | **0.954** | **0.954** | **0.000** |
| 16 | 1 | 1 | 1 | 1 | 1 | 1 | **1.000** | **-** | **-** |
| Subsystem Average | **0.923** | **0.885** | **0.908** | **0.901** | **0.910** | **0.993** | | | |
| | | | | | | **SoSRM** | **0.926** | **0.909** | |

normally increases the Forestry ($X_1$) standing stocks. Thus, the performance of $X_{2\text{-}6}$ MOP is not impacted by severing $L_{24}$. $X_1$ MOP improves because the total wood exported by $X_1$ increases. $X_1$ MOP does not incur a penalty for reducing the standing stock below the minimum allowable forestry level because Forestry level remains at the initial level (14,000 kg per capita). Although the $X_1$ MOP could be redefined, the current MOP formulation was based on the community's goal to maintain current forest size. Community decision makers felt that unsustainable activity should be avoided, but they also desired to avoid forest management issues from too large of a forest [77]. Thus, we can see counterintuitively that removing a recycling flow results in increased resilience. This scenario implies that although recycling flows may increase resilience, the implementation approach is also important. The simple integration of a recycling flow into a SoS will not guarantee an improvement in resilience (although one would still expect an increase in sustainability). A final interesting observation is that this case study provides a counterexample to the common idea that increased sustainability (by adding a recycling loop between $X_4$ and $X_2$) always leads to increased resilience.

We must also note that these results find the maximum possible improvement to SoSRM, regardless of cost or technological feasibility. For example, it may not be technically feasible to increase the paper recycling rate to 80%. The optimization search is not meant to provide actionable guidance to the KSM operators, rather this study seeks to provide a baseline allowing us to compare possible improvements from traditional resilience improvement approaches to biologically inspired network redesign.

### 4.3 Kreuzung Schweizer Mittelland Biologically inspired Improvement SoSRM.

Using Biologically inspired design alone (without optimization) increased SoSRM from 0.909 to 0.926 (Table 4). This results in an improved E[$SoSRM] savings of approximately $390,000. One cause of this increase was that the biologically inspired SoS had an additional link that the Status-Quo SoS did not have. Additionally, the added link ($L_{16}$) had no impact on constituent MOPs when removed. This outcome is logical because we would expect the SoS to have a SoSRM of 1.0 if there were no broken links. When the newly implemented link ($L_{16}$) breaks, the system reverts back to Status-Quo but without any links broken. SoSRM was recalculated to ensure that the improvement in SoSRM was not an artifact of adding a link that did not have a negative impact on constituent MOP when removed. This recalculation only incorporated the 12 links in the Status-Quo Model. The recalculated SoSRM results still demonstrated improvement from the Status-Quo SoSRM (0.909 to 0.920).

KSM SoSRM increased more from this biologically inspired redesign than from the maximum possible upgrade through traditional resilience improvement approaches (0.926 versus 0.922). This results in an improved E[$SoSRM] savings of approximately $90,000. Table 4 records the difference in link performance between the Status-Quo and biologically inspired intervention in the Delta column. The increased resilience from the broken links $L_{35}$, $L_{62}$, and $L_{61}$ drives this improved KSM performance. The reason for resilience improving due to these specific broken links is unclear and is the focus of ongoing investigations.

### 4.4 Kreuzung Schweizer Mittelland Biologically Inspired Improvement Combined With Traditional Approaches.

As a final test for this case study, the same optimization search conducted in Sec. 4.2 on the Status-Quo KSM was repeated for the biologically inspired redesigned KSM. Although traditional resilience improvement approaches were successful in increasing biologically inspired KSM resilience from 0.926 to 0.931, the gain seen in the biologically inspired case due to implementing traditional approaches was smaller than the gain seen for Status-Quo. Traditional approaches were successful in increasing Status-Quo SoSRM by 0.013, while the biologically inspired KSM SoSRM only increased by 0.005. The optimization search to find the lowest SoSRM did result in a lower value than for the Status-Quo scenario (SoSRM 0.743 versus 0.764). The Biologically Inspired Optimization search resulted in a slightly higher possible SoSRM range (difference of 0.188 versus 0.158).

Interestingly, as shown in Table 2, the optimization search for maximum SoSRM found nearly the same parameter results for the both the Status-Quo optimization and the biologically inspired optimization. We observed small differences in the PRR and minimum allowable Forestry level. This same trend is observed for the minimum SoSRM search result parameter values. Both Status-Quo and biologically inspired KSM minimum SoSRM configurations remove the Paper Recycling stream and maximizing the Forestry response lag (FLAG). This agreement indicates that although architecture changes were successful in increasing SoSRM, implementing these independently of traditional hard and soft resilience improvement approaches may be insufficient to guarantee desired SoS performance.

## 5 Conclusion

The examination of the KSM Case Study allowed us to examine our approach to sociotechnical system design, utilizing biologically inspired network design heuristics to increase SoS network resilience. Specifically, our investigation yielded four contributions:

First, we provided evidence that biologically inspired design provides an approach to increase SoS network resilience beyond current approaches. Traditional approaches struggle to increase resilience due to the emergence that manifests because of the complex interactions of humans and technology within the SoS. Optimizing traditional hard and soft resilience improvement approaches only managed to increase KSM SoSRM to 0.922, while shifting the Incinerator ($X_6$) to the decomposer functional role resulted in a higher SoSRM of 0.926. This improvement is especially significant because the optimization search for traditional resilience improvement strategies considers technological changes and investments that may not be possible (e.g., increasing PRR to over 80%).

Second, this work provides evidence that incorporating detrital actors increases SoS network resilience. Although previous studies have emphasized the importance of detrital actors within SoS, Industrial Eco-Parks, and ecosystems, the lack of a resilience metric prevented researchers from providing evidence that adding detrital actors could increase SoS network resilience. Simply by incorporating a link that transformed the Incinerator ($X_6$) from apex predator to a detrital actor, the SoSRM increased from 0.909 to 0.926. This is especially impressive because the traditional SoSRM improvements do not consider technical feasibility or cost. Our estimate of traditional resilience improvements is optimistic, expected gains when cost and technical feasibility are incorporated are expected to be much greater than the 0.027 SoSRM (E[$SoSRM] savings of approximately $90,000) observed in this study.

Third, this paper documents the first case study using the new SoSRM metric to justify a design decision. We hypothesized that transforming the Incinerator ($X_6$) subsystem from apex predator into a detrital actor would increase SoS network resilience. This hypothesis was verified, and the architecture design decision justified when SoSRM increased from 0.909 to 0.926.

Finally, this study provides additional evidence concerning the link between sustainability and resilience. Although some suggest that sustainability and resilience trend together [12,34,82], the optimization to maximize resilience recommended removing recycling from Timber Consumption to Timber Production ($L_{24}$). This balance between efficiency and resilience in this study strengthens what some ecologists theorize in sustainable natural ecosystems dynamics [83]. Removing $L_{24}$ caused a net positive increase in resilience but a negative impact on environmental sustainability. Contrasting this example, adding $L_{16}$ resulted in both an increase in sustainability and resilience. This case study provides a counterexample to the idea that increased sustainability always results in increased resilience. Further work is needed to identify the types of scenarios where adding recycling flows increases resilience.

Although this paper provides a valuable first step by illustrating the application of biologically inspired design to improve sociotechnical SoS network resilience, future studies will focus on identifying other design heuristics for implementation. Sociotechnical SoS network design is conducive to heuristics as a strategy for design, allowing the designer to apply simple guidance to improve SoS performance. Many of these may come from the field of Ecological Network Analysis, an application of graph and network theory. Additional research is focused on attempting to provide insights into the causal mechanisms behind the improvements noted when $L_{16}$ was implemented into the KSM study. These results will be replicated on other sociotechnical SoS to validate the effectiveness of the design heuristic tested in this paper. Finally, this paper examined the impact of network architecture on network resilience (following link failure), but there are other aspects of SoS performance still requiring investigation (i.e., how to ensure resilient SoS performance following rapid MOP redefinition or node removal). This work provides one area for designer consideration, but more research is needed to create a complete resilient SoS design methodology.

By analyzing KSM, this paper has presented a SoS combined of multiple complex sociotechnical systems through a network architecture. An argument was made that the constant evolution of SoS network structure coupled with the need for constituent concurrence for changes made heuristics a potentially powerful tool to improve sociotechnical SoS network resilience. Traditional design approaches are limited due to the emergence from the interacting population of independent agents, the technical artifacts in each system, and the environment. This paper presents a design methodology applied to a SoS case study that was successful in increasing the manifestation of the emergent property of resilience. This was accomplished by testing the heuristic: Seek to ensure the SoS have a constituent system that fulfills the decomposer functional role (detrital actor).

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## Conflict of Interest

There are no conflicts of interest.

## Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

## Nomenclature

$n$ = total number of subsystems within the SoS
$k$ = number of SoS links in the SoS
$T^*$ = "suitably long interval" to determine lost functionality
$T^T$ = amount of time required for 62.3% of energy to flow through the SoS
FLAG = time delay in forestry response
ForestMin = minimum allowable forestry level allowable
FPPP = production proportional controller constant
FTPP = timber production proportional controller constant
$Q(t)$ = measure of performance at time $t$
$X_6$NoPenalty = incinerator ($X_6$) storage that does not incur a financial penalty
$X_6$MaxStorage = incinerator ($X_6$) Storage that negates profits from waste management

## Appendix A: Kreuzung Schweizer Mittlelland Measure of Performance Equations

| System | MOP equation | Verbal MOP description and justification |
|---|---|---|
| Forestry | $min\begin{cases}\dfrac{\int_0^{2*t^*} L_{21}+L_{31}+L_{61}\ dt}{(L^o_{21}+L^o_{31}+L^o_{61})*2*t^*}\\ \dfrac{X_1(2*t^*)-X_1(0)}{.2*2*t^*}\end{cases}$ | Forestry ($X_1$) MOP selects the minimum from two conditions. Condition 1 is driven by business interests, while condition 2 is driven by sustainability concerns.<br>1. Forestry ($X_1$) MOP is a function of the amount of raw lumber sold to the other systems. The amount of lumber sold drives the profit the company can generate. A MOP of 1.0 corresponds to no drop in sales from the initial flow condition.<br>2. Forestry ($X_1$) MOP is the ratio of actual growth in $X_1$ stock to no disruption growth in $X_1$ stock. This metric is justified by the desire in the initial study for the KSM to maintain self-sufficiency. |
| Timber Production | $\dfrac{\int_0^{2*t^*} L_{42}\ \ dt}{L^o_{42}*2*t^*}$ | The Profit of the Timber Production ($X_2$) system is driven by the outflow of finished lumber to the Timber Consumption system ($X_4$). |
| Paper Production | $\dfrac{\int_0^{2*t^*} L_{53}\ dt}{L^o_{53}*2*t^*}$ | The Profit of the Paper Production ($X_3$) is driven by the outflow of finished paper products to Paper Consumption ($X_5$). |
| Timber Consumption | $\dfrac{X_4(2*t^*)}{X_4(0)+1.0*2*t^*}$ | Timber Consumption ($X_4$) MOP is derived from the stock of timber maintained within the system. The MOP is the stock of timber after the fault recovery as compared to the no-fault scenario. When Timber MOP falls below $X_4(0)$, Timber Consumption MOP is squared to reflect the escalating impact of increased shortages in construction supplies. |
| Paper Consumption | $\dfrac{\int_0^{2*t^*} X_5(t)\ dt}{X_5(0)*2*t^*}$ | Paper Consumption ($X_5$) MOP is derived from the stock of paper maintained within the system. The MOP is the stock of paper after the fault recovery as compared to the no-fault scenario. |
| Incinerator ($X_6$) | $\dfrac{\int_0^{2*t^*} 1-X_6(t)\ dt}{1*2*t^*}$ | The Incinerator ($X_6$) profit is driven by maximizing the amount of material processed without having a backlog of waste waiting for disposal. Backlog of material (i.e., standing stock within $_{X6}$) indicates that the Incinerator ($X_6$) is not operating at maximum capacity, thus profit is being lost. This backlog occurs when material accumulates above $_{X6}$nopenalty. There comes a point where the storage costs of material waiting to be incinerated negates the profit generated by incinerating ($X_6$MaxStorage). Once the Incinerator ($X_6$) has a backlog greater $_{X6}$MaxStorage, it is no longer making profit. The MOP compares the no-fault Incinerator ($X_6$) flow scenario to the fault scenario by monitoring the stock in $_{X6}$. |

## Appendix B: KSM Flow Equations

| Link | Differential equations (note: only positive flows) | Initial status-quo flow(kg/capita/week) | Description and reasoning |
|---|---|---|---|
| $L_{21}(t)$ | $= 4.3 - L_{24}(t - \mathrm{FLAG})$<br>$- Z_2(t - \mathrm{FLAG})$<br>$- X_2(t - \mathrm{FLAG})*\mathrm{FTPP}$ | 3.9 | Flow from Forestry ($X_1$) to Timber Production is driven by the requirements of Timber Production. Timber production ideally has zero standing stocks, so when stocks accumulate a simple proportional controller with constant FTPP = 0.1 is used to reduce the flow from Forestry ($X_1$) to Timber. $L_{21}$ flow is a function of the imports from $Z_2$ and recycling flow from $L_{24}$ The information from $Z_2$ and $X_2$ used to calculate $L_{21}$ have a time delay of FLAG = 1 week, meaning that it takes 1 week for $L_{21}$ to update to the needs of the Timber Production System. |
| $L_{24}(t)$ | $= \dfrac{(TRR * L_{64}(t))}{1 - TRR}$ | 1.7 | The recycling flow from Timber Consumption to Timber production is a function of the waste stream from Timber Consumption to the Incinerator ($X_6$). For this SoS, a timber recycling rate (TRR) of 10.5% is used. |
| $L_{31}(t)$ | $= 1.2 + L_{53}(t - FLAG) + 0.6 - L_{32}(t - FLAG)$<br>$- 4.2 - X_3(t - FLAG)*FPPP$ | 1.2 | Flow from Forestry ($X_1$) to Paper Production is driven by the requirements of Paper Production. Paper production ideally has zero standing stocks, so when stocks accumulate a simple proportional controller with constant FPPP = 0.1 is used to reduce the flow from Forestry ($X_1$) to Paper Production. $L_{31}$ is also a function of the imports from $Z_3$ and $L_{32}$. The information from $Z_3$, $L_{32}$, and $X_3$ used to calculate $L_{31}$ have a time delay of FLAG = 1 week, meaning that it takes 1 week for $L_{31}$ to update to the needs of the Timber Production System. |
| $L_{32}(t)$ | $= \dfrac{0.6 * L_{42}(t)}{2.9}$ | .6 | Flow of paper pulp from Timber Production to Paper production is a function of timber produced ($L_{42}$). |
| $L_{35}(t)$ | $= \dfrac{PRR * L_{65}(t)}{1 - PRR}$ | 2.6 | The recycling flow from Paper Consumption to Paper Production is a function of the waste stream from Paper Consumption to the Incinerator ($X_6$). For this SoS, a recycling rate (PRR) of 62% is used. |
| $L_{42}(t)$ | $= 1 + L_{24}(t) + L_{64}(t)$ | 2.9 | The timber demand is driven by the Consumption of Timber. The goal of the Timber Production is to replace losses while increasing the stock of $X_4$ at a rate of 1.0 kg per capita per week. |
| $L_{53}(t)$ | $= \dfrac{[L_{35}(t) + L_{65}(t)] * 100}{X_5(t)}$ | 4.2 | The paper demand is driven by the Consumption of Paper Products. The goal of the Paper Production is to replace losses while maintaining the stock of paper products. |

**Continued**

| Link | Differential equations (note: only positive flows) | Initial status-quo flow(kg/capita/week) | Description and reasoning |
|---|---|---|---|
| $L_{61}(t)$ | $= 1.6 + .8 - L_{62}(t - FLAG)$ | 1.6 | Flow from Forestry ($X_1$) to the Incinerator ($X_6$) is used to compensate when there is insufficient flow from Production of Timber to the Incinerator ($X_6$) to run the Incinerator ($X_6$). |
| $L_{62}(t)$ | $= 0.8 * \frac{L_{42}(t)}{2.9}$ | .8 | Flow from Timber Production to the Incinerator ($X_6$) is a function of the finished lumber produced. We also assume that if a fault removes the ability of Timber Production to send pulp paper to Paper Production, then this material is sent to the Incinerator ($X_6$) instead (not shown in equation to the left to maintain readability). |
| $L_{63}(t)$ | $= 1.1 * \frac{L_{53}(t)}{4.2}$ | 1.1 | Flow from Paper Production to the Incinerator ($X_6$) is a function of the amount of paper produced. |
| $L_{64}(t)$ | $= 1.7 * \frac{X_4(t)}{5000}$ | 1.7 | Flow from Timber Consumption to the Incinerator ($X_6$) is a function of the standing stock of timber in $X_4$. We also assume that if a fault removes the ability of Timber consumption to send recyclable material to $X_2$ through $L_{24}$, then this material is sent to the Incinerator ($X_6$) instead (not shown in equation to the left to maintain readability). |
| $L_{65}(t)$ | $= 1.6 * \frac{X_5(t)}{100}$ | 1.6 | Flow from Paper Consumption to the Incinerator ($X_6$) is a function of the standing stock of Paper in $X_5$. We also assume that if a fault removes the ability of Paper Consumption to send recyclable material to $X_3$ through $L_{35}$, then this material is sent to the Incinerator ($X_6$) instead (not shown in equation to the left to maintain readability). |
| $Z_1(t)$ | $= 6.9$ | 6.9 | The forest grows at a constant rate. |
| $Z_2(t)$ | $= 0.2 - FTPP * X_2(t)$ | .2 | Timber Production ($X_2$) ideally has zero standing stocks, so when stocks accumulate a simple proportional controller with constant FTPP = 0.1 is used to reduce the flow from $Z_2$ to Timber Production ($X_2$). Unlike Forestry ($X_1$), there is no lag (FLAG) assumed with this process. |
| $Z_3(t)$ | $= 0.9 - FPPP * X_3(t)$ | .9 | Paper Production ideally has zero standing stocks, so when stocks accumulate a simple proportional controller with constant FTPP = 0.1 is used to reduce the flow from $Z_3$ to Paper Production. Unlike Forestry ($X_1$), there is no lag (FLAG) assumed with this process. |
| $Y_6(t)$ | $(1 + X_6(t)) * 6.8 * \frac{L_{62}(t) + L_{61}(t)}{2.4}$ | 6.8 | The Incinerator ($X_6$) outflow is driven by two factors. First, the system is designed with zero standing stocks, so if $_{X6}$ accumulates, $Y_6$ $_{increases}$. Second, $L_{62}$ and $L_{61}$ provide the fuel for the Incinerator ($X_6$), thus outflow is also limited by the available fuel. |

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