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Introducing Flexibility to Complex, Resilient Socio-Ecological Systems: A Comparative Analysis of Economics, Flexible Manufacturing Systems, Evolutionary Biology, and Supply Chain Management

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Received: 8 December 2016; Accepted: 19 June 2017; Published: 22 June 2017

Abstract: In this paper, a framework incorporating flexibility as a characteristic is proposed for designing complex, resilient socio-ecological systems. In an interconnected complex system, flexibility allows prompt deployment of resources where they are needed and is crucial for both innovation and robustness. A comparative analysis of flexible manufacturing systems, economics, evolutionary biology, and supply chain management is conducted to identify the most important characteristics of flexibility. Evolutionary biology emphasises overlapping functions and multi-functionality, which allow a system with structurally different elements to perform the same function, enhancing resilience. In economics, marginal cost and marginal expected profit are factors that are considered to be important in incorporating flexibility while making changes to the system. In flexible manufacturing systems, the size of choice sets is important in creating flexibility, as initial actions preserve more options for future actions that will enhance resilience. Given the dynamic nature of flexibility, identifying the characteristics that can lead to flexibility will introduce a crucial dimension to designing resilient and sustainable socio-ecological systems with a long-term perspective in mind.

Keywords: flexibility; resilience; sustainability; socio-ecological system

1. Flexibility: A Popular, Diverse and Ambiguous Concept

Systems found in the biological arena and social sphere are complex [1,2]. The biological and socio-economic worlds are filled with elements with small structures being part of bigger schemes with multiple structures. The multiple components are interconnected via multiple pathways, which gives rise to a complex system [1,2]. These systems are also uncertain and not deterministic in nature, with multiple types of perturbation affecting them, which can be either sudden shocks or slow changes. These shocks can be external or internal in nature and can have adverse effects on the system. Slow external changes include climate change, whereas natural disasters are typically considered to be shocks. Slow internal changes can arise from poverty or inequality, whereas an internal shock can take the form of an economic depression or armed war.

Resilience is one of the common perspectives used in socio-ecological and complex-system research. Academics from different fields, including sustainability science, have readily employed the theory of resilience and its definition. Resilience as a metaphor and its definition are sometimes incommensurable with the theory of resilience, as they have different definitions and standards, and the term has been co-opted for different agendas [3]. The theory of resilience (and its definitions) used in sustainability science has been developed by ecologists and is not without criticism. One argument from the social sciences is that resilience and complex systems frameworks perpetuate the idea of functionalism; system ontology; equilibria, and thresholds; use of rational actor and conservative approaches to sustainability [4]. Further, they do not consider the instability created within the system [3]. In addition, the tendency to see resilience as a desirable outcome has been questioned [4]. To counteract these criticisms and accommodate interdisciplinary research on complex systems and socio-ecological systems, both critics and proponents of these approaches have called for pluralistic approaches [5].

Given the uncertain shocks and disturbances, it is necessary for a system to have the ability to change and accommodate to them, or risk system failure. Flexibility is considered as the property of a system that promotes change in the system [6]. In an uncertain world, the daily lives of people are prone to certain risks. Understanding and managing these risks is critical for citizens, governments, and businesses to plan their future operations and ensure medium and long-term sustainability. Humans form social networks and are highly enterprising, which makes us adaptable. However, present day lock-ins, be they technological, institutional, or behavioural, have major ramifications on the future sustainability and resilience of a system. The ability to change a system is pertinent in overcoming these lock-ins. In the present paper, the idea of flexibility is used in connection with the concept of resilience to explain their importance for research on sustainability. Although the need to consider flexibility has already been made in the literature on resilience, this link has not been explicitly emphasised. Flexibility is a concept that, although often used, is not yet widely discussed within the context of sustainability, resilience, complex systems, and socio-ecological frameworks, despite its multiple features which can enhance such frameworks [7]. Perspectives on flexibility can be informed by looking at similar notions in economics, biology, management, and engineering systems. In the present paper, we propose that flexibility is a crucial property which is necessary to make systems resilient (where resilient systems are defined as those that have the ability to cope with an uncertain stress or strain). Based on a literature review on resilience, we argue that robustness and transformation are two parameters that are crucial for a resilient system. Flexibility, which is the ability to change, leads to both robustness and transformation in times of stress or strain. Flexibility is thus a property of a system which promotes change within the system [6]. Hann et al. listed the multiple interpretations of flexibility and flexibility-like words (such as adaptability, resilience, or robustness) commonly used in academic literature. They give a nuanced understanding of their use, highlighting the multiple and overlapping meanings of these terms [8]. At the same time, flexibility is used within the academic literature as a term with its general dictionary meaning. Flexibility as a concept is very useful but ambiguous and diverse, and thus requires explanation in order to introduce it as a fundamental concept when discussing complex, resilient socio-ecological systems. We identify certain characteristics of flexibility to add value by presenting a conceptual framework where the idea of flexibility is introduced into the resilience framework, expanding the current understanding of how it can be used in the field of sustainability science. To do so, we delve into the literature on resilience. The latter part of the paper then places stress on the need for flexibility as a property for resilience, including a literature review of flexibility from flexible manufacturing system, economics, evolutionary biology, and supply chain management to elucidate different characteristics of flexibility. We build on both ontological and conceptual linkages between flexibility and resilience thinking from the four fields mentioned above. Flexibility alternatively can also have negative repercussions. However, in the present paper, we conceptualise flexibility in conjunction with both robustness and transformation. Nevertheless, we focus on flexibility and the characteristics of flexibility which can lead to possible ideas and pathways to escape the lock-ins which can prevent transformation and adaptation. The features of flexibility are prescribed as toolkits which should be used based on the context of the systems or the problem analysed. Also, we list down the importance of concepts like flexibility, resilience, and other concepts like complex sytems, transitions, and path-dependency, as they have the potential for integrating research on sustainability. These concepts and terms can be used for conceptual coordination. We argue that this is necessary to move beyond the debate on the dichotomy of unification and pluralism within sustainability sciences.

2. Resilience—From Static to Dynamic

Academics from different fields have widely accepted the resilience thinking, and the number of papers on resilience in the web of science exploded to 800 in 2013, from 60 in 1993 [9]. These papers come from a wide variety of fields like sociology, urology, environmental sciences and ecology, history, anthropology, polymer science, urban studies, materials science, amongst others. Thoren (2014) contends that the concept's abstractness has allowed it to permeate different fields, with the possibility of unifying some of them [9]. Earlier, the concept was used in the areas of psychology and material science; recently the concept is being used in sustainability science. In this sense, it is worth noting that the widely accepted definition of resilience used in sustainability science was first developed by ecologists [10].

Holling defines stability as "the ability of a system to return 'to an equilibrium state after a temporary disturbance; the more rapidly it returns and the less it fluctuates, the more stable it would be" [10]. Similarly, Holling defined resilience as, "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" [10]. Resilience has a dynamic character, though stability emphasises returning to a static state.

Clark identifies the core sustainability program as "understanding the complex dynamics that arise from interactions between human and environmental systems." However, traditional research on sustainability focuses on problem-solving from an individual vantage point [11]. Since the biological and socio-economic realm's exhibit complex dynamics, the concept of resilience is apt to study dynamism.

There are three different articulations of resilience, namely ecological resilience, engineering resilience, and the adaptive cycle of resilience. "Engineering Resilience" emphasises the time a system takes to return to equilibrium or a steady state [12]. This definition would appear to be identical with the term elasticity, as understood in the field of engineering [13], and is more in line with the definition of "stability." However, defining resilience as a steady state condition allows it to lose its dynamic character. When applying this concept on a global level, Gunderson accepts the implicit assumption in engineering resilience that there is only one steady state [14]. Nevertheless, this articulation is popular in some academic disciplines, especially in the field of disaster management [15]. However, it is questionable if, given the deplorable condition of particular systems; it is advisable to bounce back to the original system [16]. Many disaster management programs and studies focus on the recovery of an area's population, economy, or built form to its pre-disaster state (though this view is slowly changing with the application of "build-back-better" principle, see for example) [17].

Ecological resilience differs from the disaster management concept in that it accepts the presence of multiple stability regions. The main parameter measured is the amount of perturbation which the system can absorb. However, some researchers interpret "ecological resilience" just like "engineering resilience", without taking into account the dynamic nature of resilience [18]. Nevertheless, generally speaking, ecological resilience accepts the dynamic character of the resilience; though this dynamic nature is restricted within the boundaries of these multiple states. This definition does capture the idea of continuous change, with multiple stability regions. The different states and stability condition of three various types of articulation of resilience are summarised in Table 1.

Table 1. Types of Resilience.

Resilience	States	Stability Condition
Engineering Resilience	Single Basin	Single Stability Range
Ecological Resilience	Multiple Basins	Dynamic with multiple Stability Range
Adaptive Cycle	Cyclical Process	Dynamic and continuous

Finally, the idea of the adaptive cycle of resilience captures the concept of continuous change, which was extended into resilience literature by Holling and Gunderson [19]. The adaptive cycle has four stages, namely, exploitation (r), conservation (K), release (Ω), and reorganisation (α), as shown in Figure 1. The fore loop of the process typically takes place during a longer time than the others, and involves movement from exploitation/growth to the conservation stage, and is characterised by increased connectedness and stability. After the conservation phase, the system disintegrates in a back loop to the release stage and then reorganises to reach the growth stage, completing the cycle.

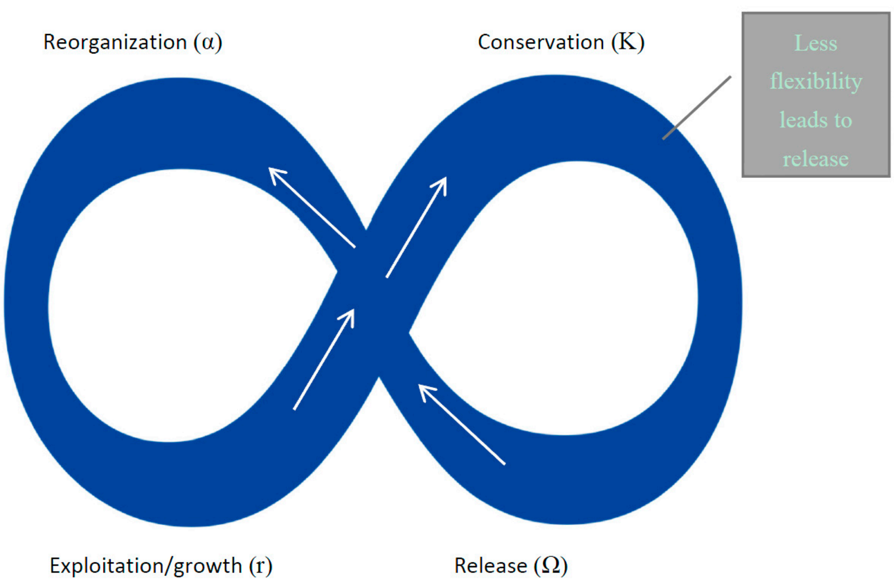

Figure 1. Adaptive Cycle.

In conclusion, the concept of resilience in sustainability science has transformed gradually from referring to a single stability region into a dynamic and continuous system, which more accurately captures the essence of the real world. From an evolutionary approach, it is hard to imagine an equilibrium state given the large number of parameters typically involved in such complex systems, all of which are constantly changing. A resilient system should be able to absorb perturbation given the uncertainty and unpredictability of a system. The concepts of adaptive cycle and ecological resilience incorporate this impression of dynamism and allow for continued adaptation and transformation as one of the best ways of facing uncertainties.

In 2002, Carpenter suggested the following three possible aspects of resilience, (i) response to disturbance; (ii) capacity to self-organize; and (iii) capacity to learn and adapt [20]. Similarly, Holling (1986) pointed out the importance of renewal, novelty, innovation, and reorganisation of a system while extending the concept of resilience to a socio-ecological system [21]. However, Walker et al. (2004) and later Folke (2010) emphasised additional critical characteristics of a resilient system under a framework that they referred to as "resilience thinking." Folke noted that adaptability and transformation are necessary features of a resilient system [22,23]. Adaptability has been used in resilience literature as "the capacity of actors in a system to influence resilience" [22]. Walker et al. (2004) defined transformability, "as a means of defining and creating new stability landscapes by introducing new components and ways of making a living, thereby changing the state variables, and often the scale, which defines the system."

As described earlier, the traditional view on resilience gives importance to the persistence of a system, with Folke et al. noting the dichotomy between robustness and resilience [23], where "confusion arises when resilience is interpreted as backwards looking, assumed to prevent novelty, innovation and transitions to new development pathways. This interpretation seems to be more about robustness to change and not about resilience for transformation."

By focusing on the backward-looking features of engineering resilience, adaptability and transformation can be neglected, while comparing resilience with the vulnerability framework, Miller et al. added that "similar trends can be seen in the resilience literature, in which empirical work is still interpreting resilience in the narrow sense of return time and recovery, thereby missing the broader use of the concept" [24]. Resilience in that sense can be broadly broken as having two parameters: the backwards looking features like robustness and adaptation, and forward-looking feature like innovation and transformation of resilience. It is necessary to study the system to appreciate the dynamic and continuous change that it goes through as a whole, and incorporate adaptation, transformation, and robustness instead of narrowly interpreting it. Carlsson contends that there is a highly formal and abstract work on flexibility in academia [25], with Bateson defining flexibility as "uncommitted potentiality for a change" [26]. Similarly, within the resilience literature, the importance of flexibility was stressed [22]:

"As the K phase continues, resources become increasingly locked up, and the system becomes progressively less flexible and responsive to external shocks. It is eventually, inevitably, followed by a chaotic collapse and release phase (Ω) that rapidly gives way to a phase of reorganisation (α), which may be rapid or slow, and during which, innovation and new opportunities are possible" (Figure 1 for reference).

However, the concept of flexibility is not well developed within resilience. In the following section, the authors attempt to develop a conceptual framework that will highlight the importance of flexibility in the resilience building framework.

3. Flexibility—Balancing the Extreme Needs of a System

In this section, we introduce our new conceptual framework, emphasising the role of flexibility in creating resilience, as illustrated in Figure 2. The concept of flexibility from fields such as biology, engineering, and economics is used to organise the ideas within the resilience thinking framework, which constitutes the originality of the present paper and the concepts it seeks to introduce. In this context, the relationships within a system—which can be both robust and able to evolve—can be elaborated. The authors contend that flexibility as a property leads to both robustness and transformation, which are two parameters that are crucial for a resilient system. Table 2 summarises these relationships.

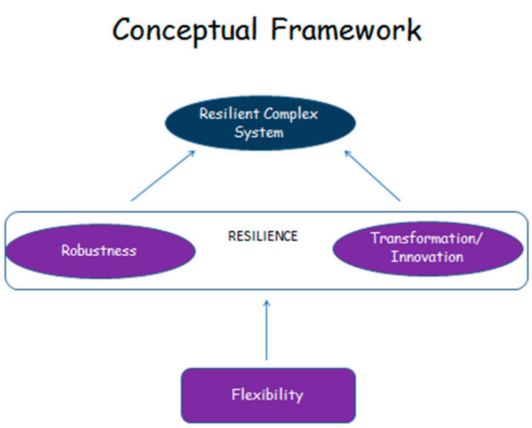

Figure 2. Illustration of the relationships between flexibility and a complex system.

Table 2. Relationship between Flexibility and Variables.

Variables	Relationship	Relationship	Reference
Robustness	More parts and pathways	Flexibility allows higher chance of survival	[27]
Transformation	More interactions	Flexibility facilitates the interaction	[28,29]

Robustness and innovation are both necessary for a system. Robustness is important in the context of the present, though innovation becomes necessary in the framework of the future. Edelman and Gally note that in systems which are planned, robustness is introduced by incorporating redundancy to known externalities [30]. In the event of an unknown externality, Edelman et al. (2004) note that the flexibility of a system is crucial in maintaining its robustness. Also, the same flexibility is essential in realising innovation within the system. Similarly, Ferguson et al. (2007) contend that flexibility can manifest itself as multi-ability, evolvability, or robustness. Evolution reflects the ability of the system to be reconfigured [6]. Robustness reflects "optimal performance or maintenance of some level of functionality." These ideas are similar to those by Edelman and Gally (2001) and later Whitacare (2010) [30,31].

The combination of existing parts within a system is considered as a critical process for innovation. Numerous examples in the field of biology prove the presence of combination to produce novelties. For example, Andreas Wagner cites the example of combinations of chemical reactions in the creation of life [28]. Solee et al. (2013) reviewed biological and technological evolution and emphasised that they are driven by the reuse and combination of existing resources. They stress that, unlike biological evolution, technological innovation can be planned [29]. Systems created by humans from the perspective described above can aim for higher performance, taking into account both resilience and flexibility [29]. A transformative system has a higher potential not to become vulnerable and fragile to stress and strain.

Blau and Schwartz (1984) stressed that societies, where individuals do not have any group affiliations, would have the highest social integration [32]. It is also implied that for a complex idea to spread it was better to reduce social boundaries. However, this could mean that in a highly diverse population with no social boundary there would be people with no common interest, leading to an erosion of social networks. Damon Centola argues that social integration when there are no group boundaries is important up to a point [33], though after a certain threshold it is important that group boundaries be maintained, which allows a population with similarities to create and diffuse ideas. Diffusion of an idea to groups outside the group's boundaries would be possible by the interaction of members in overlapping groups. Ulanowicz similarly argues that there is the sweet spot in the degree of connectedness in a system, and he contends that this can be observed in all natural systems [34].

Robustness and the ability to transform are relevant parameters for successful systems, as explained in previous sections. A complex system is better able to provide robustness and innovation. Robustness and innovation within the system are only possible if the system can change. A system which is inflexible or locked in has a major possibility of suffering catastrophic damage under episodic events for which it is not prepared. It is in this context in which the flexibility of a system becomes crucial. Hence, a system which can be actively changed can be robust under stress and shock. Flexibility, in that case, is an essential property of a system within resilience. Similar ideas have been used to conceive products which are both flexible and reconfigurable [6].

Carlson & Doyle (2002) emphasised that the commonly held belief that complex systems are not robust is false [27]. They present the analogy of a simple bacterium. Simple bacteria have several hundred genes in comparison to *Escherichia coli*, which has ten times the genes present in simple bacteria. Thus, the simple bacteria can only survive in highly regulated environments. *E. coli*, on the other hand, can survive in a wide range of environments. Similarly, they also present the example of an older automobile which has simple systems, while newer vehicles have complex systems with airbags, an antilock-breaking system, anti-skid systems, and so forth. The newer automobiles are safer and more robust in comparison to the earlier automobiles. Thus, using both of these examples, they point how inherent complexity can drive robustness in the system [27]. A complex system with flexibility can transfer the resources needed from the point of surplus to deficit in times of stress or strain, making the system more robust.

An organism or system has to balance between robustness and transformation in response to the changing condition in the environment. The example of the caterpillar is often cited. Caterpillars need to maintain robustness in terms of functioning and at the same time accommodate the changes in genes required to transform them into butterflies [35]. Similarly, the same ideas can be applied to the cultural and social sphere, where different concerns to stabilise the system and transform them require that a balance between these needs are struck [35]. These examples point out the importance of balancing the competing extremes, and how robustness and transformation are competing characteristics of any system and flexibility can play a major role. Flexibility allows the transfer of flows in a system, where the flow can be the movement of goods, knowledge, financial capital, and so forth. Such flows will allow for transformation, which will result in new products or ways of doing things. Transformation is severely hindered in a "locked-in system", which will prevent innovation and possibly make a system vulnerable to changes in the long run.

4. What Are the Characteristics of Flexibility?

Flexibility as a concept has been described in the economic, engineering, and biological realm. However, up to this point, it is not clear what flexibility is within the resilience framework, as described by Walker et al. (2004) [22]. In the present paper, the authors would thus like to introduce the concept of flexibility as a critical property of resilience. Flexibility is at the core of a resilient system, allowing it to become both innovative and robust, and can create a system which is both innovative and robust. Here we review the idea of flexibility from different disciplines, listing its features.

4.1. Flexibility from Supply Chain Management

Goranson defines flexibility as the "scheduled or planned adaptation to unforeseen yet expected external circumstance" [36]. Rice and Caniato defined redundancy as an additional capacity which could be used during the capacity loss, whereas flexibility refers to rerouting during a disruption of committed capacity elsewhere [37]. Sheffi and Rice define redundancy as "resources in reserve to be used during disruption", and flexibility as organic capabilities that can sense threats and responds to them quickly [38]. Tomlin defines flexibility as a contingency action that is carried out in the case of disruption, whereas redundancy is a mitigation action which is taken in advance [39]. Since the supply chain deals with connecting different value chains, flexibility within this field reflects the same ontological presuppositions.

From such definitions, it is clear that redundancy focuses on creating additional stock and buffers, whereas flexibility emphasises on rerouting flows or functions in situations of stress or shock. A flexible system will help to weather a crisis by achieving a better use of existing resources. However, this does not mean redundancy is not critical, rather that with increased flexibility such resources can be utilised in an optimum way. In contrast to redundancy, the emphasis is on the creation of pathways. Here, flexibility is discussed as being more akin to creating robustness (resilience) in the system, with a short-term focus.

4.2. Flexibility from the Field of Economics

In the area of economics, Stigler (1939) was the first to define "flexibility", which centred on the idea that a flexible firm was able to make profits given changing exogenous demand [40]. Later, Carlsson defined flexibility as those attributes of a production technology which accommodate greater output variation. He discussed flexibility regarding the cost curves of companies: flexibility varies inversely with the curvature of the total cost. If the average total cost curve is U-shaped, the flatter it is and the more slowly marginal cost rises, the greater the firm's flexibility [25]. Similarly, Stigler views flexibility from the economic angle, where he finds a system/firm with a flat marginal cost curve as flexible.

Hart and Mills looked at flexibility from the view of demand fluctuations [41,42]. At a systems level, Mills and Schumann contended that "small firms are able to compete successfully with large, more static efficient producers by absorbing a disproportionate share of industrywide output fluctuations. This is possible because small firms use production technologies that are more flexible than those chosen by large firms. Large firms (have) lower minimum average costs, due largely to scale economies, while small competitors have an offsetting advantage in their superior responsiveness to cyclical or random swings in demand" [43].

Mills and Schumann contend that big businesss are static producers and Small Medium Enterprises (SME) are dynamic producers. It is the SME which adds the flexibility that is desirable to the system. When conceptualising a flexible approach, this dialectic nature of large and small firms can be incorporated. Though literature from the field of economics deals with demand fluctuation and cost curves, it was Marschak and Nelson (1962) who extended the idea to include [44];

(1) The size of choice set: a more flexible initial action preserves more options for movement in the following periods.
(2) Marginal cost: a more flexible plant requires the less additional cost to move towards the next position (essentially the view of Stigler [40]).
(3) Marginal expected profit: a more flexible plant generates more profits or smaller losses in moving to a new position. (essentially the view from Carlsson [25]).

The earlier ideas of flexibility have been dominated by cost and demand fluctuation. The ideas proposed by Marschak and Nelson broaden them by including the size of choice sets. The discussions on flexibility are based on the "firm" level, and the emphasis on fluctuation and cost curves is oriented towards the creation of short term robustness. The ideas of Marschak and Nelson (1962) highlight the transition phase of resilience (transformation), with a long-term focus.

4.3. Flexibility from Flexible Manufacturing Systems

Flexible Manufacturing Systems (FMS) have revolutionised the way that manufactured goods are produced. Concerns about flexibility have existed for a long time, though there has been a general belief that flexibility and efficiency/productivity have trade-offs, and it was not until the 1960's that the FMS was adopted by companies and plants [45,46]. Sethi & Sethi (1990) added that, "the efficiency of the mid-volume, mid-variety production is largely accomplished by a drastic reduction or elimination of setup costs and times required for switching from the production of one product to another" [47].

Flexibility arose as it was considered one competitive strategy, along with the price, dependability, and quality of the product [48]. According to Hayes & Schmermer, this flexible strategy should "consist of a sequence of decisions that, over time, enables a business to achieve a desired manufacturing structure (i.e., capacity, facilities, technology, and vertical integration), infrastructure (i.e., workforce, quality, production planning/material control, and organisation), and a set of specific capabilities (that enables it to pursue its chosen competitive strategy over the long term)."

The literature review carried out by Sethi and Sethi (1990) broadly classified flexibility into ten categories, though some of these are almost identical [47]. According to these authors, the following are properties which reflect flexibility;

- Ability to have different functions, without resulting in prohibitive costs
- Reach outcomes through different/alternate ways
- A set of the results which can be attained without any addition to the system
- Ability to run the system at different output levels
- Ability to expand capacity and capability when needed
- The ability of the system to run virtually untended for a long enough period.

These characteristics can be applied to make a system flexible and responsive to uncertainties and eventualities. Flexibility can be seen to be connected with resilience in both the short and long term. The flexibility perspective emanating from FMS, like in the field of economics, is considered from a firm's perspective. However, the economic perspective focuses on the "cost" of operating the firm, while the FMS's focus is on the "operations" of a firm. These two can be seen to be complementary approaches.

4.4. Flexibility from Evolutionary Biology

Biological organisms adapt well to new conditions by developing new traits, with the concept of degeneracy playing a key part in such processes. In this sense, Edelman defines degeneracy as, "the ability of elements that are structurally different to perform the same function or yield the same output is a well-known characteristic of the genetic code and immune systems. Here, we point out that degeneracy is a ubiquitous biological property and argue that it is a feature of complexity at genetic, cellular, system, and population levels. Furthermore, it is both necessary for, and an inevitable outcome of, natural selection" [30].

It is well documented that degeneracy leads to biological flexibility, as degenerate systems have components which are multi-functional and have partially overlapping functions [31].

Edelman and Gally (2001) contend that it is this characteristic of a biological system which has been crucial in evolution, as these features allow for adaptation, which is necessary for survival in the environment given the uncertainties in the biological world [30]. Conventional designs developed by engineers involve a modular approach. Edelman and Gally hold that it is conceivable that complex degenerate systems can be used by engineers, given developments in nanotechnology and electronics, and the reduced cost of electronic chips and memories. However, the understanding of degenerate systems is inadequate at this point of time, and it is not known how such systems are linked and synchronised at different levels.

Whitacre et al., (2010) add that the engineering elements are designed for a specific purpose and that one-to-one mapping does not exist in the biological world [31]. In their view, degeneracy can be separated into functional redundancy and functional plasticity. Functional redundancy is defined as the characteristics of many-to-one mapping between components and functions [31]. On the other hand, functional plasticity is defined as the features of one-to-many mapping between components and functions. Whitacre adds that systems with trade-offs between efficiency and robustness (short term sustainability) do not arise due the functional plasticity (one-to-many mapping). In such systems, elements which are excluded from participation in one function move to another, and as this happens excess energy is also shared between the different processes. If plasticity and redundancy are considered together, this entails the presence of dissimilar components performing similar functions at certain times and doing other functions at different times. It is possible for the components to be functionally redundant and at the same time functionally distinct, as per the requirements or needs of the system.

Whitacre stresses that degeneracy leads to a complex hierarchical system with both robustness and evolvability. Evolvability and robustness are both needed in a biological population, where organisms have to be robust in different environments and at the same time evolvable to adapt to a new environment. Evolvability and robustness are complementary and do not stand alone. Similarly, in human societies, social and economic systems that are both innovative and resilient are needed. Care should be taken when applying this concept to complex social systems, as degeneracy has been studied concerning genotypes and phenotypes, not sustainability science. Nevertheless, degenerate systems with components which are multi-functional and have partially overlapping functions can play a major role in creating resilient systems. The discussion on flexibility in evolutionary biology can be seen at multiple scales: genetic, cellular, system, and population levels. This is different to supply chain management, economics, and FMS, which focused only on the supply chain and firm levels, respectively. In addition, the role of the whole and parts are reflected. This approach reflects the connection of flexibility to the whole (organism, system) and the parts (traits), with an empahsis on overlapping and multifunctionality at different scales.

4.5. Flexibility and Resilience

In this section, we describe the difference in conceptualising the relationship of flexibility and resilience between the fields of economics, flexible manufacturing systems, evolutionary biology, and supply chain management. In supply chain management, there is a clear separation between redundancy and flexibility. Redundancy focuses on creating additional stock and buffers. Flexibility, on the other hand, emphasises rerouting flows or functions. However, for a resilient system to come about, it is necessary to focus on both stocks and flows. The different qualities of flexibility mentioned in various disciplines are summarised below in Table 3.

Table 3. Flexibility in different disciplines.

Academic Discipline	Focus
Supply Chain Management	Focus on flow like functions and rerouting
Economics	Cost and demand fluctuation initially and later addition of decision making
Flexible Manufacturing Systems (FMS)	Connecting decision making with desired manufacturing structure, infrastructure and capabilities over a long term
Evolutionary Biology	Degeneracy has been an inevitable outcome of natural selection

In the field of economics, the initial concept of flexibility focused on cost and demand fluctuation. Later, scholars broadened them by including the size of choice sets by focusing on decision-making and strategy. However, this emphasis on decision making and strategy are more developed in FMS. In FMS, flexibility arose as it was considered one competitive strategy, along with the price, dependability, and quality of the product. One of the major focuses was on connecting decision-making with the desired manufacturing structure, infrastructure, and capabilities over the long-term within the factory setup.

The conceptualisation of flexibility in evolutionary biology comes from degeneracy, and it is argued that degeneracy is an inevitable outcome of natural selection. The concept emerges from the functioning of cells and genes in the genetic code and immune systems. Two qualities of degenerate systems are multi-functionality and overlapping functions. The concept of degeneracy gives valuable insights into the behaviour of biological systems, and Whitacre argues that it positively correlates with robustness and evolvability [31]. Similarly, the previous subsections highlight how our understanding of flexibility has moved from demand fluctuation in the field of economics to one that broadly covers various issues, as summarised in Table 4.

Table 4. Flexibility in Different disciplines.

(1) Economic Flexibility	(2) Degeneracy	(3) Engineering Flexibility
The size of choice set Marginal cost Marginal expected profit	Components with Multi-functionality Overlapping functions	Ability to have different functions without prohibitive effort Reach outcomes through different/alternate ways A set of the results which can be attained without any addition to the system Ability to run the system at different output levels Ability to expand capacity and capability when needed The ability of the system to run virtually untended for a long enough period.

Overall, the understanding of flexibility in the fields highlighted in Table 4 is both converging and diverging, thus enriching the concept with a diverse set of ideas. There are overlaps between degeneracy and flexible manufacturing system (FMS), as both have operationalised components with overlapping functions and multi-functionality as a property: (1) The ability of the system to have components that have multiple functions leads to lower marginal costs under uncertain conditions; and (2) the size of the choice set is similar to the number of pathways a system can take. The size of the choice set is more attuned towards increasing the capability of the system. Increasing choice options result in a more capable system, in the form of the number of pathways it can take. These can create both robustness and lead to transformation within the system.

The following characteristics from FMS can be seen to increase the choice sets: (1) the ability to run the system at different output levels and the ability of for it to run virtually untended for long enough periods allows for robustness. The system has the potential to work at various output levels, which is necessary when the systems are under stress or strain, (2) the ability to expand capacity and capability when needed is also useful while thinking about the transformation potential of the system. A minimum condition while implementing these properties is that a system should have minimum marginal expected profits or should make lower losses. The characteristics mentioned above are summarised below in Table 5.

Table 5. Flexibility in Resilience thinking framework.

Robustness (Persistence)	Innovation (Transformation and Adaptation)	Both
Ability to run the system at different output levels The ability of the system to run virtually untended for a long enough period.	Marginal cost Marginal expected profit Ability to expand capacity and capability when needed.	The size of choice set Overlapping functions Multi-functionality. Reach outcomes through different/alternate ways A set of the results which can be attained without any addition to the system

The ontological focus of these disciplines is on different functions, units, and temporal scales while connecting flexibility and resilience. For example, functionally the focus is on the following: movement of materials in supply chain management; cost in economics; decision making and operations in FMS; and robustness and evolvability in evolutionary biology. The focus of FMS on decision making and operations allows a wider and better understanding of the system or process. In the case of evolutionary biology, with degeneracy, the focus is on operations and functions which are seen to be an inevitable outcome of natural selection. The temporal focus of FMS, economy, and evolutionary biology is both long and short term. The term “short” and “long” has a normative essence, with each having diverse connotations in different fields. SCM on the other hand is more focused towards short term. Likewise, each discipline focuses on different units: supply chain in supply chain management, a firm in economics, a firm in FMS and genetic, cellular, system, and population levels in degeneracy. A major impetus of flexibility in all the four disciplines has been its dynamism. This is brought about by looking into the “dynamism” of pathways to external disruptions in supply chain. In economics, this is shared with cost and production consideration due to external demand, though the emphasisis on SME adds that flexibility is created by the “dynamism” of the SME. Such conceptualising of what constitutes a flexible approach is based on the dialectic nature of large and small firms. Also, FMS incorporates and considers both internal and external shocks to a firms as threats, and flexibility is seen to be a competitive strategy in a “dynamic” world. Degeneracy is also attached to the same “dynamic” environment. Thus, flexibility is anchored on “dynamism”, in comparison to the old notion of “static” resilience. It is the “dynamic” flexibility which can allow both “static” and “dynamic” resilience. This is important, as a “static” resilient system cannot infuse “dynamism” i.e lack of flexibility that can lead to a lock-in. In a globalised world with global value chains, flexibility can lead to innovation and robustness within the network of organisations by promoting competitiveness and collaboration, thus playing a strategic role in the path towards sustainability through supply chain management, public policy, and corporate strategy [49].

5. Agenda for Research—From Lock-Ins (Inertia) to Resilience Thinking and a Flexibility Toolbox

Currently, thinking on how to increase the resilience of socio-ecological systems is dominated by seven principles which focus on connections, managing connectivity, maintaining diversity and redundancy, polycentric governance, fostering complex adaptive thinking, broaden participation, and encouraging learning [50]. One major difference between redundancy and flexibility is that redundancy focuses on creating additional stock and buffers, while flexibility emphasises rerouting flows or functions, overlapping functions and multi-functionality, many options or alternatives for decision making and marginal cost while creating flexibility options. Such an analysis will not only help in its use to identify the system and policies which are flexible but also determine the ones that are not flexible. For example, there are several debates regarding whether flexible labour market, flexicurity, and other similar programs are really flexible [51].

Here we list two examples of multifunctional and overlapping features of flexibility. The first case regards the role of knowledge-intensive services in the economy, and the second is about flexible landscape management. Knowledge-intensive services include functions like computer services, engineering services, consulting services, R&D, and so forth. These services help in transferring the information and knowledge in the form of a horizontal flow of information. The horizontal nature of the transfer flow allows knowledge to be disseminated to peers, who then accelerate the diffusion of knowledge to the entire economy [28]. This interplay is reflected in the knowledge-intensive services, as it allows the mixing of knowledge from diverse fields. For example, consultancy firms typically employ individuals with different skill sets, and there is a greater possibility of creating novel thoughts or ways of doing things. Companies with a workforce with multiple and overlapping functions can create novelty, and at the same time, its employees can hold cross-functional posts. Since a knowledge-intensive service sector is critically dependent on knowledge, this movement of human resources is crucial for its continuity. These services then influence the ability of a country to manufacture goods and produce new services, which in turn depends on the interconnectedness and interactions of diverse stakeholders within the economy. Also, it is necessary that there is diffusion of knowledge and variance in the knowledge held within an economy. In contrast to serendipity, innovation also takes place in the form of recombination of existing knowledge, and can sometimes have an incremental character. The existing information becomes crucial for both incremental knowledge and recombination of existing knowledge to take place. Countries with a higher information and knowledge base have a better chance to recombine or incrementally improve their existing knowledge [52].

Rural and urban landscapes in Europe are strictly separated, and these ideas have increasingly been adopted all across the world. Increasingly, researchers have focused on the peri-urban landscapes in Europe, which they argue is becoming more flexible than the set of rules that rigidly differentiate the theoretical boundary between rural from urban areas. The agricultural lands in peri-urban areas spaces are now used for biodiversity conservation or outdoor recreation or put to commercial and recreational use as horse paddocks or golf courses [53]. Such opportunities in planning allow multi-functionality of these landscapes in peri-urban landscapes, increasing the list of beneficiaries. The green wedge project at Stockholm and the model forest Vilhelmina are examples of this approach. These projects do not have a 'final goal' but rather focus on the process of provisioning the long-term sustainability of the landscape with multiple functions through dialogues with different stakeholders. Such an approach also caters to the need of allowing greater "choice sets and options" in decision making. Just like the strict separation between urban-rural landscapes, in the context of landscape management and conservation, the prevailing view supports "sustainable intensification", through an intensification of monoculture with a strict separation for agricultural and conservation purposes. We acknowledge the importance of debates around intensification and efficiency while opening an argument for flexibility. Multiple functional landscapes, aside from practical ecological benefits, also have overlapping social benefits. Diverse multifunctional landscapes are open to a broader list of beneficiaries, and these beneficiaries are more local [54].

However, there are lock-ins which hinder these approaches to become mainstream. Seto et al. (2016) note how institutional, technological, and behavioural lock-ins have created a carbon lock-in [55–57]. She further stresses that "undoing or escaping carbon lock-in will require undertaking significant initiatives and investments in the near term while retaining the flexibility to adapt, refine, and replace those initiatives and investments in the long term."

Seto et al. (2016) add that "institutional plasticity and flexibility is needed to overcome this institutional lock-in similarly" [55]. She further adds that "a transformative theory of institutional change must identify both factors that create permissive conditions for such change to occur and self-conscious processes that promote institutional change given those conditions."

Thus, it is clear that research on themes related to human behaviour and institutional and technical flexibility to achieve sustainability transitions can help to add new perspectives on how to break the lock-ins and thus help in transformation and adaptation. This is of great importance for public policy and corporate planners to make plans and implement decisions that take longer-term sustainability into consideration.

Critics of resilience or the systems approach point out that the ontological presupposition with functionalism; system ontology, equilibria and thresholds, use of rational actor and conservative approaches to sustainability are not popular among social scientists [4]. At the same time, mainstream economists that have an ontological focus on methodological individualism do not take into account the complexity of reality [58]. Environmental social science and humanities have diverse ontologies and frameworks that are incommensurable [59]. The planetary boundary paradigm presents us a framework incorporating the need for "continued development of human societies with the maintenance of the Earth System (ES) in a resilient and accommodating state" [60]. Even if there is no ES collapse, the global connectivity among different actors and institutions can have global impacts [61]. There is a need to address the issue of ES thresholds with human agency and structure, which inhibit continued human development and maintenance of ES. Given the complex reality, it is important to incorporate the idea that "Part makes whole, and whole makes part" [62]. This dialectic relation between part and whole has implications for sustainability science. Systems (whole) consist of parts which are heterogeneous and have no existence alone. Parts interact with each other, giving a certain shape to the whole. On the other hand, the whole has certain features of its own, which impacts the parts. While concepts used in economics, management, and engineering have a "systems" focus, they invariably understand certain parts of the whole. Environmental issues are a classic example of complexity. Human institutions and structure have been responsible for climate change and this has a certain impact on the ES. At the same time, climate change and other ES systems have their own character and impacts on individuals and communities. Research on sustainability science should reflect this dialectic nature of whole and parts. Such an approach can also help in moving away from the extremes of reductionism and holism, and help in interdisciplinary and cross-disciplinary approaches. Further, these approaches can be used by integrating both quantitative and qualitative research as stated:

"Progress is not from qualitative to quantitative. Quantitative description of a system is not superior to qualitative understanding. When approaching complexity, it is not possible to measure "everything," plug it all into a model and retrieve intelligible results. For one thing, "everything" is too big. Qualitative understanding is essential in establishing quantitative models. It intrudes into the interpretation of the result" [63].

The concept of planetary boundaries and systems thinking allows conceptualisation of resilience at the global scale. The concept of resilience thinking and other "reductionist" approaches have been seen to focus on the species or community level in ecological studies, and on the individual level in social science studies [64]. Resilience thinking approaches have an appeal at both the local and global scales. A framing of resilience with both adaptation and transformation can incorporate both conservative and radical approaches to sustainability. However, in these instances resilience has been used as a metaphor. In comparison to the unification approaches, sustainability science has been enabled by problem-feeding from one discipline to another, and this approach has led to pluralism [65]. Pluralist approaches can still have language barriers which might not allow for conceptual coordination. Trading zones and interactional languages are needed, where researchers can create concepts like creole language or pidgin, which can help to facilitate the problem and solution-feeding [66]. Integration, in comparison to the dichotomy of unification and pluralism, can be facilitated by use of concepts, methods, and explanations [67]. This is necessary since "construct pluralism" can crowd the academic landscape with many definitions of the same word [68]. There are many concepts which can help in this integration of research, though there needs to be a better conceptualised understanding of these terms. Elaborating further on integration is beyond the scope of this paper. We hold that resilience and flexibility have the potential for integrating research on sustainability by using them for conceptual coordination. For doing so, primary changes have to be made to the concept of resilience, with some coherence among its usage. Some steps have already been taken in that direction with work on resilience thinking with governance [69], institutional theory [70], public administration [71], and structuration theory [72]. In this paper, we have attempted a similar exercise by informing about notions of flexibility by looking at similar notions in economics, biology, management, and engineering systems.

6. Conclusions

Flexibility refers to the property of a system to change, and a system which can actively change can be robust under both stress and shock. Flexibility allows immediate deployment of resources where they are needed and hence will lead to less damage and quick recovery. The present research looked into a dynamic conceptual approach required to appreciate the importance of flexibility in creating systems that are resilient and sustainable. It is important for a system to be both robust and transformative, just like an organism has to balance between robustness and transformation in response to changing conditions in the environment. Similarly, a system has to balance between the extremes of robustness and transformation, and flexibility characteristics, if embedded in a system, can allow for such a balance between extremes. Flexibility has a vital role to play in such a system and can be used as a lens to study it. Adopting such a perspective of studying flexibility in itself can allow the development of systems that are both robust and transformative in nature and open a different way to study resilience within the field of sustainability science.

In this paper, a framework incorporating flexibility as a characteristic is proposed for designing complex, resilient socio-ecological systems. In an interconnected complex system, flexibility allows the prompt deployment of resources where they are needed and is crucial for both innovation and robustness in a resilient system. A comparative analysis of flexible manufacturing systems, economics, evolutionary biology, and supply chain management is conducted to identify the most important characteristics of flexibility. Evolutionary biology emphasises overlapping functions and multi-functionality, which allow a system with structurally different elements to perform the same function, enhancing resilience. In economics, marginal cost and marginal expected profit are considered essential in incorporating flexibility while making changes to the system. In flexible manufacturing systems, the size of choice sets is important in creating flexibility, as initial actions preserve more options for future actions that will enhance resilience. We illustrate two cases of this, namely the knowledge intensive services and multifunctional landscapes to elucidate the role of flexibility thinking. The features of flexibility are prescribed as toolkits which should be used based on the context of the systems or the problem analysed. Given the dynamic nature of flexibility, identifying the characteristics that can lead to flexibility will introduce a crucial dimension to designing resilient and sustainable systems from a long-term perspective.

Acknowledgments: We acknowledge MONBUKAGAKUSHO (MEXT), Government of Japan, for their financial assistance for this study. This research did not receive any other specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Author Contributions: Vivek Anand Asokan conceived the idea and carried out the literature review. The manuscript was written by Vivek Anand Asokan in close association with Masaru Yarime. Further, Masaru Yarime and Miguel Esteban provided conceptual and editorial inputs while drafting and editing the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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