The Development of an Integrated Model for Assessing Sustainability of Complex Systems

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ABSTRACT
Synergetic interaction of factors such as financial management, supply chain management, process management, research and development, strategic marketing and sales, employee and customer relations, etc. contribute to business success. Aligning business with principles of sustainable development (SD) is considered a worthwhile goal by many in the SD arena. One significant advantage with the alignment is the potential for enhanced resilience to shocks that may disturb income generating activities. However, there is growing awareness that sustainability of the Earth as a system needs to be considered when attempting to sustain business. This awareness may be significant for the survival and well being of the human species in the long term. Assessment of sustainability is an essential step in determining if action taken is sustainable. Early research in sustainability assessment was based on reconciling the three pillars (environmental, social and economic). Today there are numerous indicators (single and composite) for measuring impacts in the three pillars though current thinking emphasises the need for system thinking rather than the reductionist concept of pillars. Most existing indices/methods measure single aspects of sustainability and the more integrated indicators are aimed at national or global level assessments. A review of existing indicators, methods and models within the context of complex system sustainability showed that no single existing index, method or model was able to assess sustainability of complex systems. This is because most fail to account for complex system characteristics such as system dynamics, interconnections and interdependencies of system components, a system's ability to learn and remember, emergence of novel behaviours, co-evolution, etc. This paper presents the methodology used to develop a new model for assessing sustainability of complex systems based on risk.

1. INTRODUCTION

A complex system consists of large populations of independent, interacting and self-interested agents where behaviour of the whole cannot be explained by the behaviour of the individual parts (Sawyer, 2005). Examples of complex systems include the weather, political parties, stock market, etc. (Nonaka and Nishiguchi, 2001; Gell-Mann, 1994). From complex system theory stemmed Complex Adaptive System (CAS) theory where a CAS is a system that is complex and adaptive giving it the ability to change and learn thus increasing chances of its survival. The Earth system is an example of a CAS (Holland, 1995; Norberg and

Cumming, 2008), and organisations are CAS within the Earth system (Waldrop, 1992). The adaptive cycle (Figure 1) is the "fundamental unit of dynamic change" in a complex system (Gunderson and Holling, 2002). It describes the process of development and decay of a system and contains within it four phases – exploitation (r), conservation (K), release (Ω), and reorganization (α) (Holling and Gunderson 2002). This work also outlines three properties of an adaptive cycle: 1) Inherent potential for change; 2) Internal degree of connectedness, flexibility, or rigidity; and 3) The adaptive capability or resilience of the system.

The word "panarchy" was coined to represent the nature of adaptive cycles which are nested hierarchically within each other (Holling, 2001; Gunderson and Holling, 2002). Figure 1 illustrates the most important adaptive cycle in terms of sustainability where sustainability is defined as "the capacity to create, test and maintain adaptive capability". According to Levin (1998), complex systems are resilient as they resist change or change slowly. Basically, a system maintains stability because it is protected by slow conservative changes in larger systems above it, while being energised by faster changes in smaller systems below it. Critical conditions within levels can cause disruptions between levels and destabilise the system. The "revolt" and "remember" cycles are significant at times of change. "Revolt" occurs at the **Ω** phase where a level in the panarchy experiences a collapse. The cascading effect can cause disruptions to larger and smaller levels triggering a crisis. The "remember" cycle draws information, energy or resources from the slow and larger levels to facilitate renewal.

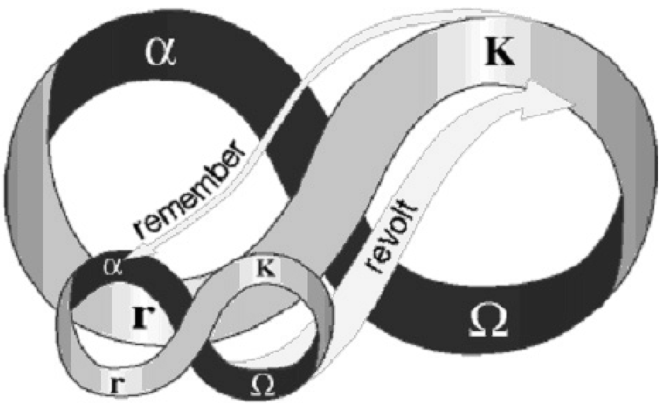

Figure 1: Panarchy – revolt and remember cycles (Holling et al., 2002a)

1.1 The Research

The objective of the research was to develop a model that is able to assess sustainability of a CAS by taking properties of CAS, such as the adaptive cycle, into account. The research method for developing the model is as follows:

- **Step 1:** Review complex systems theory to determine the basic criteria required for sustainability;
- **Step 2:** Review existing sustainability assessment models and methods to determine if they assess sustainability according to the criteria found in step 1;
- **Step 3:** Develop a new model to assess sustainability by integrating the most appropriate existing models so as to capitalise on their strengths, minimise individual weaknesses in addition to meeting the criteria for sustainability; and
- **Step 4:** Test the new model on case study products.

This paper presents the final model developed at Step 3 where the risk assessment (RA) and Life Cycle Assessment (LCA) are the two methods integrated. Steps 1 and 2 which lead to the choice of RA and LCA are briefly outlined here and are expected to be presented in subsequent papers. Some results from Step 4 can be found in Babarenda Gamage and Boyle (2006), Babarenda Gamage and Boyle (2008) and Babarenda Gamage et al. (2008).

2. CHARACTERISTICS OF COMPLEX ADAPTIVE SYSTEMS

According to Holling et al. (2002, pp 396), sustainability "is maintained by relationships among a nested set of adaptive cycles arranged in a dynamic hierarchy in space and time – the panarchy". Identifying characteristics of complex systems and how they interact may be useful for sustainability of complex systems (Raskin et al., 2002) given that "sustainability is the capacity to create, test, and maintain adaptive capability" (Holling et al., 2002b, pp 403). Having an understanding of complex systems is significant for policy making towards changes for sustainability (Munn, 1995). Therefore, understanding the patterns and function of complex systems, and thus making appropriate changes in some areas (e.g. product development (McCarthy et al., 2006) and organisational change (Dooley, 1997), etc.) may help increase resilience and adaptive capacity (Holling, 1996; Gunderson and Holling, 2002; Walker et al., 2004) and, thus, human survival. The characteristics of CAS need to be addressed or at least acknowledged in order to understand sustainability of the complex system. Following that, they also need to be addressed when assessing sustainability. Some of the significant characteristics of complex systems are given in Table 1. Note that there are many more characteristics such as randomness (Bonabeau et al., 1997), crosscutting hierarchical interaction (Arthur, 1997), fractal behaviour (Morales-Matamoros, 2010), edge of chaos/out-of-equilibrium dynamics (Arthur, 1997; Langton, 1991), feedback loops and learning (Arthur, 1996), etc.

Table 1: Characteristics of complex adaptive systems

Characteristic	Description of Characteristic	Reference
Aggregation (Holism)	Complexity emerges from the interactions of agents or systems.	Holland (1992), Arthur (1995)
Nonlinearity	Agents interacting in non-linear ways such that the outcomes of interactions are not proportionate.	Holland (1992)
Flows, local interactions, connectivity	Agents are organised into networks where interactions can trigger other interactions.	Holland (1992), Levin (1998)
Diversity	Agents evolve to fill certain niches and the greater the variety of agents, the stronger the system can be.	Holland (1992), Levin (1998), Kinzig et al. (2002)
Emergence	Dispersed interaction of agents acting in parallel result in patters that emerge which informs the behaviour of the agents as well as the behaviour of the system.	Arthur (1997), Holland (1998)
Co-Evolution	Systems are part of the environment and exist within their environment hence as the environment changes, the systems also changes and when the system changes, the environment is also changed.	Kauffman (1980), Ghersa et al. (1994)
Self organisation	"Order for free" - there is no command and control hierarchy but there is constant re-organising in order to determine the best fit in the environment in which the	Waldrop (1992), Kauffman (1980)

	system functions.	
Dynamic	Agents and connections are not fixed in time but may be dynamic and change as conditions change. The resulting pattern reflects change, learning and adaptation.	Holland (1995)
Resilience	The capacity to maintain function by absorbing shocks. It is also the ability for renewal and re-organisation	Gunderson and Holling (2002)

Significant characteristics of complex systems are used as criteria to evaluate existing sustainability assessment methods and models. The evaluation is aimed at determining whether existing methods and models are able to assess CAS; and failing that, to identify methods and models that are able to take into account some of the characteristics of CAS. The criteria used to evaluate existing methods and models are:

1. Take complexity of the system into account by:
    a. Recognising the existence of multiple agents and system levels;
    b. Recognising interconnections and interdependencies;
    c. Taking system dynamics into account (time and space);
    d. Recognising system limits or thresholds;
    e. Recognising resilience and adaptive capacity; and
    f. Being holistic; and
2. Be based on science where appropriate.

The second criterion was added to help achieve scientific validity.

3. EVALUATING SUSTAINABILITY ASSESSMENT METHODS AND MODELS

The criteria above were used to evaluate 26 existing sustainability assessment methods. These methods consist of analytical tools (e.g. cost benefit analysis, etc.), indicator based methods (e.g. Living Planet Index, Well Being Index, etc.) and integrated methods (Ecological Footprint, triple bottom line (TBL), etc.). The evaluation results showed that while the existing methods and models were successful at assessing the aspects of a system for which they were designed, they are unsuitable for tackling complex systems hence do not assess true sustainability. They do not incorporate enough of the necessary criteria thus fail at being holistic. The evaluation also highlighted a number of potential methods and models that may be beneficial if integrated as a new model. Eight existing methods and models, all of which have at least two of the seven criteria necessary for assessment of complex system sustainability were analysed further. These methods and models include risk assessment (RA) (analytical tool); ecosystem resilience (integrated method); Sustainable Process Index (an indicator); Life Cycle Assessment (analytical tool); Product Sustainability Index (an indicator); Ecological Footprint (integrated method); barometer for sustainability (integrated method); and Sustainability Assessment by Fuzzy Evaluation (SAFE) (integrated method), and may hold the key to assessing sustainability of complex systems.

Generally, all of these tools may be integrated together and some of these tools may be extended in terms of their boundaries and scope to enable them to include characteristics of complex systems that are just beyond their reach. For example, LCA may be extended to allow for the social and economic dimensions to be analysed thus improving its abilities in terms of becoming a more holistic tool. Choosing the most appropriate methods for integrating was based on factors such as whether:

- The assessment methods have been standardised;
- Literature as guides exist and are readily available;
- It is used for education, planning and policy development;
- Databases for the methods exist;
- Research with respect to the assessment method has to its own academic journal (i.e. indicating whether there is high volume of research in progress);
- The assessment methods and their results are widely communicated and accepted;
- The assessment method comprises of the necessary characteristics to be integrated (i.e. if there have been previous attempts to integrate); and
- The assessment methods complement each other.

The results of the evaluation showed that LCA and RA had many of the required characteristics and thus appropriate for integration.

4. NEW MODEL FOR ASSESSING SUSTAINABILITY

The basic framework for the new model is given in Figure 2. Since LCA and RA have been standardized, the standards (ISO 14040, ISO 14044, AS-NZS 4360-2004, ISO/IEC 31010:2009) together with handbooks (Guinée et al., 2002; Baumann and Tillman, 2004; etc.) can provide information and instruction on some of the elements to be addressed for parts of this model.

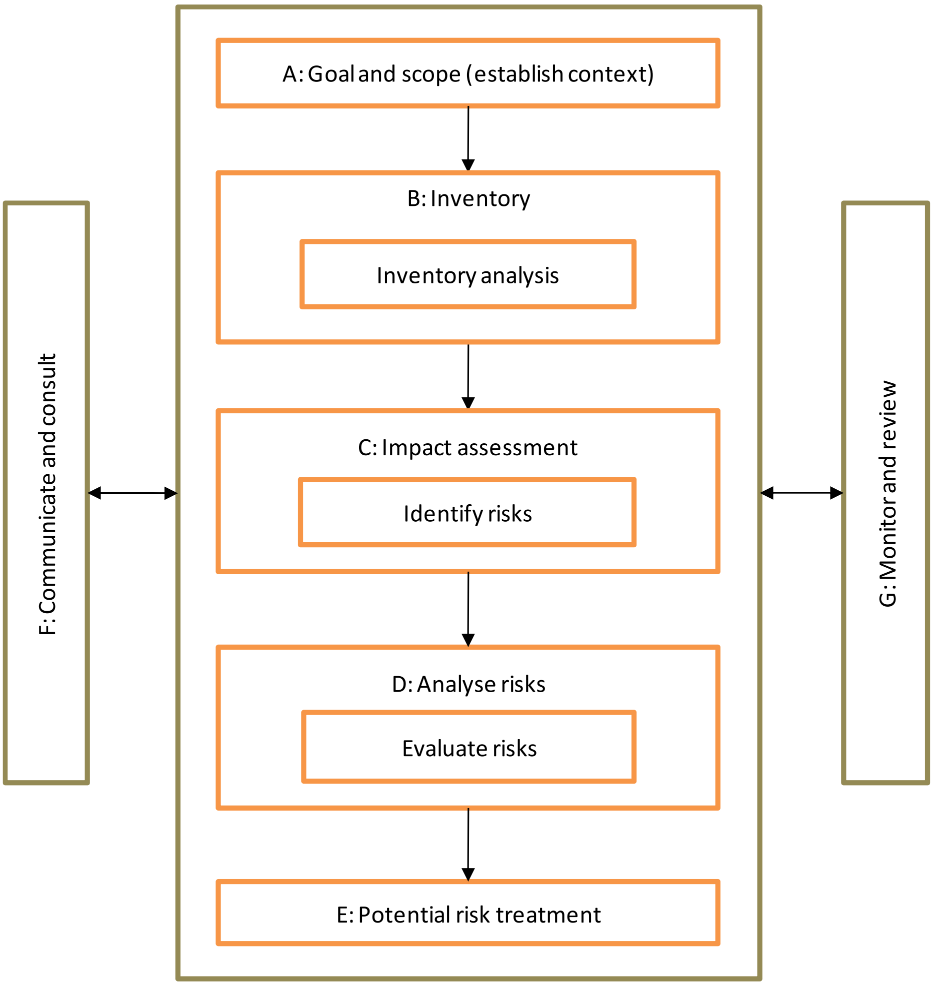

Figure 2: Sustainability assessment framework integrating LCA and RA

In terms of the practical implementation of the model, the extent of the study can be defined with respect to the expectations of the practitioner and commissioner of the study. The audience of the results depends on the purpose of the study. For example, if the study is conducted for improvement of a product, then the audience can range from the Board of Directors of the company to the design team where higher level buy-in may be useful for changes to occur. The model is to be applied to a Small and Medium size Enterprise (SME) but should be transferable to any product system. The simplest (reduced) version of the model is given in Figure 3. This is equivalent to a triple bottom line type model where the environment, social and economic systems have been reduced into three separate systems. A further reduction of the streamlined model in Figure 3 can be undertaken by concentrating on one type of system risk. However, this would defeat the purpose as the reductionist approach fails to account for the complexity by neglecting the interconnections and interdependencies with respect to the other systems.

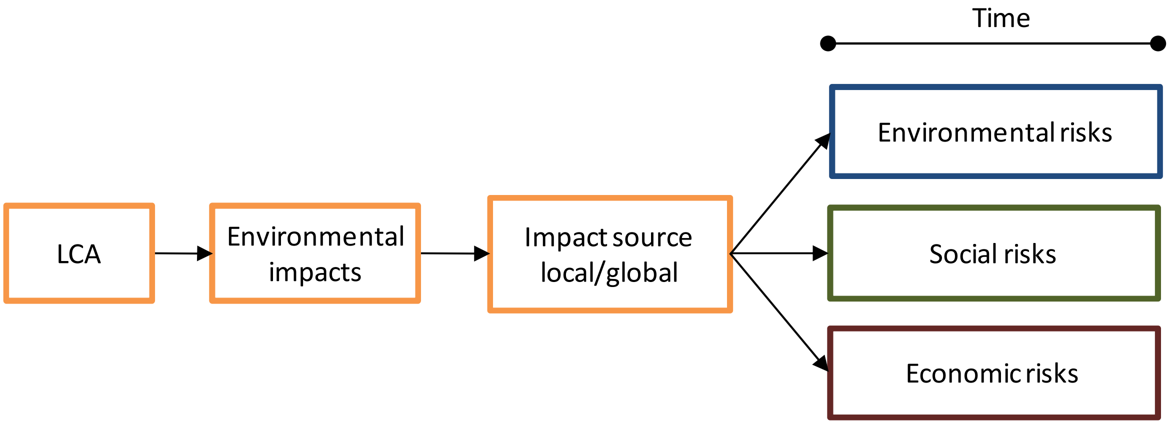

Figure 3: Streamlined sustainability assessment – reduced to three systems

While the model in Figure 3 may allow the identification of risk in different systems, it does not allow these risk events to be connected with the other systems. Often, a risk in one system propagates into another, but this model would not be able to make the appropriate connections across different system levels. This model can be modified according to the strong sustainability model (Brekke, 1997; Neumayer, 2003) as shown in Figure 4.

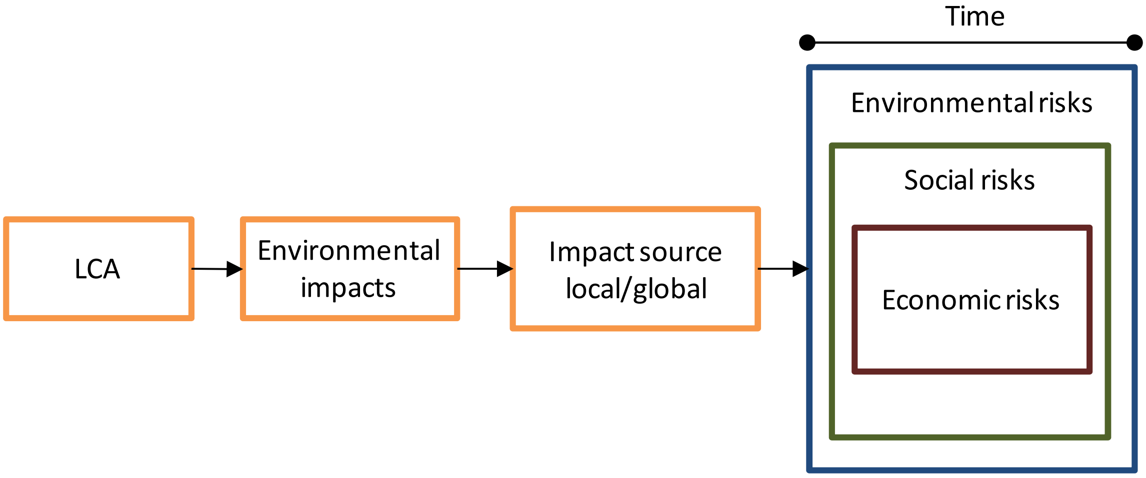

Figure 4: Streamlined sustainability assessment

Since the version of the model given in Figure 4 starts off with one set of data, i.e. environmental data for LCA, it is still a streamlined version. However, while this is still a streamlined version, it is able to trace the interconnections among the risks from the environmental, social and economic systems. In order to upgrade this model to a full holistic version, social and economic data are requires as input. Figure 5 shows the pathways for full sustainability assessment. Data concerning the three systems are used to calculate impacts for each system with respect to spatial differentiation. This is done separately up until the RA stage where risks are identified and analysed together with the interconnections. This model would entail the use of three separate databases, each similar to those required for the models in Figure 3 and Figure 4. While the assessment model in Figure 5 can accommodate most of the interconnections among the systems at the risk assessment stage, it still separates the three systems at the beginning thus remains to be reductionist to some extent.

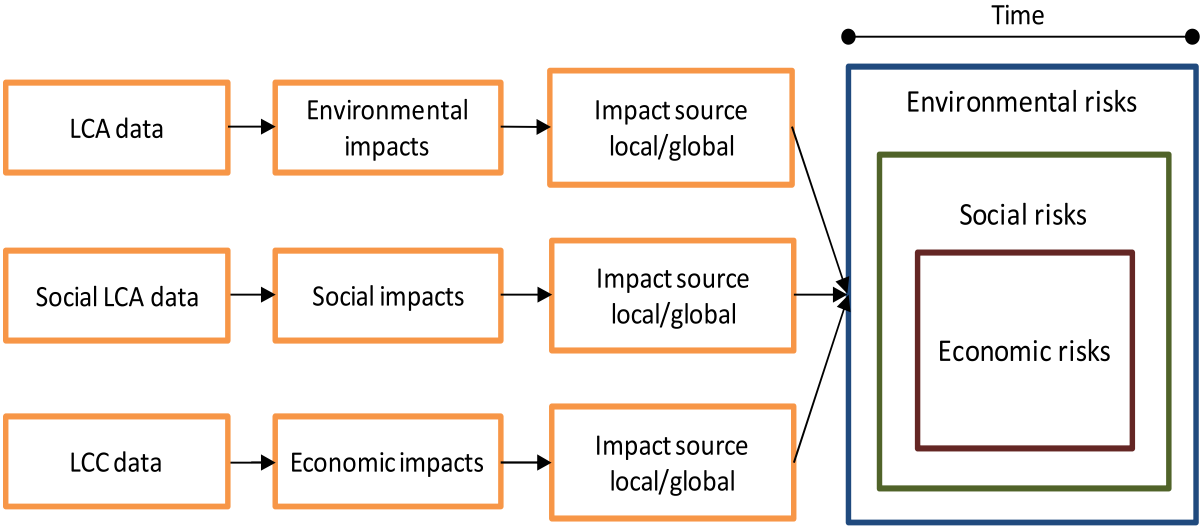

Figure 5: Sustainability assessment comprised of streamlined assessments per system

A fully integrated sustainability assessment would require the interconnections at each step to be taken into account. I.e. the inputs and outputs of all the relevant data would be integrated into a single inventory; the connections among the different types of impact categories would be made via cause-effect chains together with the respective locations of the impacts; and subsequently, the resulting set of risks would also highlight the interconnections among the various systems together with time (Figure 6). Each box in the figure represents complex interactions. This is not the same as adding the assessment of the three systems separately as interaction of inputs and outputs would be at a deeper and holistic level where there is little or no segregation of systems. As with the reduced versions of the model, the practitioner is able to choose which systems will be included in the assessment as per the goal of the study. The choice of input data (inventory), the type of impacts (i.e. impact categories) and risks to assess (i.e. environmental, social or economical) depends upon the goal of assessment. The main difference between this model and the earlier ones is that this would be able to illustrate the interconnections more effectively and holistically from beginning to end.

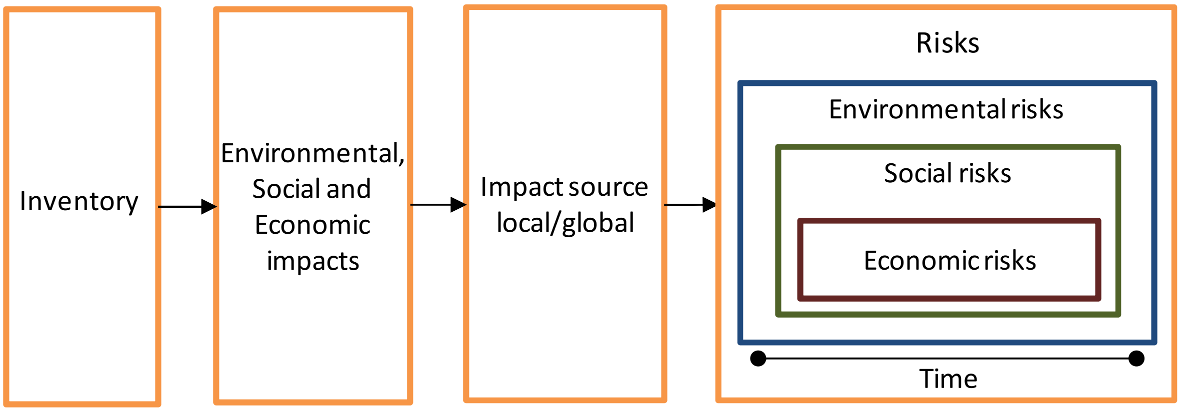

Figure 6: Complete sustainability assessment

5. RESULTS FROM THE MODEL

The model results in three levels of risk or threat identification that are connected through different system levels. The three levels of risks are:

1. Risks from smaller lower level systems (micro level) - risks within the product system as well as risks to the product system from systems below;
2. Risks from the larger upper level systems (macro level); and
3. External risks from random disasters – risks from emergence.

The risks can be categorised according to the incoming and outgoing threats as shown in Figure 7. The outgoing risks (arrows in black) relate to the threats associated with the impacts found at the impact assessment step of LCA and consist of external or global risks affecting the larger systems. The incoming risks (arrows in red) indicate the risks to the inner systems propagating from larger upper level systems. The evaluation of the identified risks and the subsequent treatment of those risks are expected to aid sustainability of the complex system.

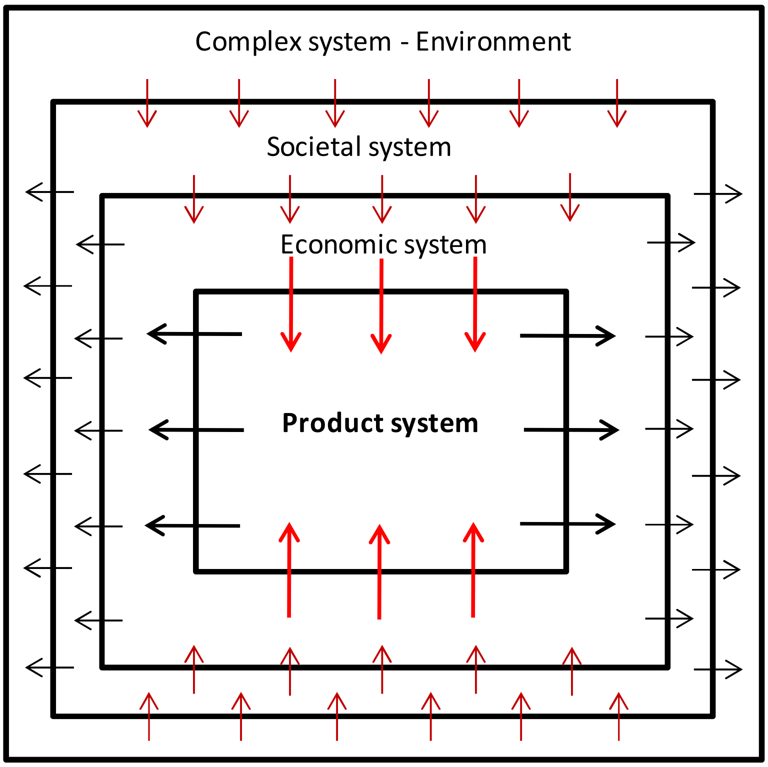

Figure 7: Incoming and outgoing risks related to the CAS

6. CONCLUSIONS AND FUTURE WORK

The final model presented in the chapter is a hybrid model that uses the results of one component of the assessment, the LCA, as input data for another component (RA). The model progresses from a reduced version consisting of streamlined assessments with respect to the systems chosen for assessment, to a holistic version which encompasses all three relevant systems (environmental, social and economic) from initiation (inventory) to completion (risk evaluation).The model follows the LCA steps with integrated inventory up until impact assessment spanning all three system after which the impacts are analysed to determine the risks from the chosen impact categories. The impact are also analysed to determine the significant sources of the impacts and how these impact sources can threaten the system. There are various ways of streamlining the assessment, ranging from using separate data records in the inventory to reducing the risks according to each system. Failure of the streamlined assessment is expected due to the negligence of interconnections. Future work may consist of practical implementation of the full model, together with investigating whether mitigation of identified risk would indeed lead to sustainability.

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