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Strategic Engineering for Cloud Computing and Big Data Analytics

Springer

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Foreword

The first time I got involved in a rigorous problem-solving effort related to system resilience and strategic engineering was during my internship at Intel, Santa Clara. As a Ph.D. student, my main concern at school was to build functional chips, chips that simply work as I powered them up. But at Intel Skylake Server CPU group, for the first time, I was facing questions about the reliability of the server chip, the back-end platform of cloud computing and big data management, in an uncertain, perhaps distant future. The following questions were the main considerations:

- How can we foresee the failures and avoid (or delay) them during the design stage?
- What type of failure is more likely to happen in a specific block of the system?
- What are Mean Time to Failure (MTTF) and Mean Time Between Failures (MTBF)?
- How can we maintain and dynamically correct our system while it is running?
- How can we expand and scale the system with new software and hardware features without jeopardising reliability, sustainability and security?

The short exposure to strategic engineering had a long lasting impact on my approach toward engineering in general and integrated circuits and systems design in particular. Later that autumn, when I returned to my tiny damp cubicle at building 38 of MIT to continue working on nano-relay based digital circuits, my concern was no longer merely the functionality of my systems right out of the box. The durability, scalability, resilience and sustainability of the system started to play an important role in my design strategies and decisions.

In the new age of global interconnectivity, big data and cloud computing, this book provides a great introduction to the flourishing research field of strategic engineering for cloud computing and big data analytics. It encompasses quite a few interesting topics in this multidisciplinary research area and tries to address critical questions about systems lifecycle, maintenance strategies for deteriorating systems, integrated design with multiple interacting subsystems, systems modelling and analysis for cloud computing, software reliability and maintenance, cloud security and strategic approach to cloud computing.

While many questions about the future of big data in the next 20 years are unanswered today, a good insight into the computational system modelling, maintenance strategies, fault tolerance, dynamic evaluation and correction and cloud security would definitely pave the way for a better understanding of the complexity of the field and an educated prediction of its future.

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Preface

This first edition of Strategic Engineering for Cloud Computing and Big Data Analytics focuses on addressing numerous and complex, inter-related issues which are inherently linked to systems engineering, cloud computing and big data analytics. Individuals have consistently strived through engineering and technology to improve the environment on a global scale. With this ever-changing societal environment, there are far greater challenges which are required to address these phenomenal technological evolutionary demands.

The primary audience for the book is research students, industry experts and researchers in both industry and academia, masters level students, undergraduate students who are interested in the subject area with a view of gaining greater understanding and insight in the strategic implications of cloud computing in terms of big data analytics additionally managers wishing to gain a better understanding of introducing and implementing new improved technology concepts within their organisations. This book is particularly relevant for readers wishing to gain an insight into the overall constructs of systems engineering in line with the growing dimensions of cloud and big data analytics. It covers a wide range of theories, techniques, concepts, frameworks and applied case studies related to key strategic systems development, maintenance and modelling techniques.

The subject of strategic engineering is far too complex for such simple solutions and therefore the book provides a critical and reflective systems thinking approach. The book is particularly useful in illustrating an opulent foundation of materials which clearly and objectively draw upon a number of examples and real-world case studies in order to demonstrate the many key issues facing the ever-changing technological environment we live in today.

There are three key parts the book focuses on. Part I focuses on 'Systems Lifecycle, Sustainability, Complexity, Safety and Security'; Part II focuses on 'Systemic Modelling, Analysis and Design for Cloud Computing and Big Data Analytics' and the final Part III focuses on 'Cloud Services, Big Data Analytics and Business Process Modelling', focusing on strategic approaches, with the onus on cloud services and big data analysis. The fundamental direction of systems engineering is unpacked around 12 chapters, which consider the process of evaluating the outcomes of the key parts outlined above. The chapters provide significant level of depth for the reader with an emphasis of providing a clear understanding of system reliability, system design analysis, simulation modelling, network management protocols, and business intelligence tools for decision-making processes.

Finally we consider the current challenges in the multidisciplinary field of strategic engineering namely the future direction of systems engineering and the way it is shaped to match and complement the global environment, the changing societal needs, the challenges faced by business and the key policy drivers as well as the technologies that these future systems undertake. The technological advances aligned with the basic fundamental components, their subsystems and infrastructure will no doubt create and increasing leap into the future leading to erudite services and products. The book is structured in such a way so as the readers can follow the book, chapter by chapter sequentially or they can 'dip into' the book chapters as they please.

The main emphasis of the book is the fundamentals of strategic engineering by outlining the trends on the ground rules for through-life systems with a view of addressing simulation modelling in line with the systems engineering constructs. The book introduces 12 chapters and presents interesting and insightful discussions in terms of the growth in the area of cloud and big data analytics, dealing with phenomena such as software process simulation modelling for agile cloud, the impact of business intelligence on organisations and strategic approaches to cloud computing. The individual chapters included in each part of the book are briefly summarised.

Chapter "Mathematical and Computational Modelling Frameworks for Integrated Sustainability Assessment (ISA)" focuses on outlining generic mathematical and computational approaches to solving nonlinear dynamical behaviour of complex systems. The goal of the chapter is to explain the modelling and simulation of system's responses experiencing interaction change or interruption (i.e., interactive disruption). Chapter "Sustainable Maintenance Strategy Under Uncertainty in the Lifetime Distribution of Deteriorating Assets" considers random variable model and stochastic Gamma process model as two well-known probabilistic models to present the uncertainty associated with the asset deterioration. Within Chapter "A Novel Safety Metric SM_{EP} for Performance Distribution Analysis in Software System" the focus is primarily on safety attributes becoming an essential practice towards the safety critical software system (SCSS) development. Chapter "Prior Elicitation and Evaluation of Imprecise Judgements for Bayesian Analysis of System Reliability" examines suitable ways of modelling the imprecision in the expert's probability assessments. Chapter "Early Detection of Software Reliability: A Design Analysis" takes the approach of design analysis for early detection of software reliability. Chapter "Using System Dynamics for Agile Cloud Systems Simulation Modelling" provides an in-depth background to cloud systems simulation modelling (CSSM) and its applicability in cloud software engineering—providing a case for the apt suitability of system dynamics in investigating cloud software projects. Chapter "Software Process Simulation Modelling for Agile Cloud Software Development Projects: Techniques and Applications" provides an overview of software process simulation modelling and addresses current issues as well as the motivation for its being—particularly related to agile cloud software projects. This chapter also discusses the techniques of implementation, as well as applications in solving real-world problems. Chapter "Adoption of a Legacy Network Management Protocol for Virtualisation" discusses, with examples, how network management principles could be contextualised with virtualisation on the cloud. In particular, the discussion will be centred on the application of simple network management protocol (SNMP) for gathering behavioural statistics from each virtualised entity. Chapter "Strategic Approaches to Cloud Computing" outlines strategic approaches to cloud computing with the focus on cloud providing business benefits when implemented in a strategic manner. Chapter "Cloud Security: A Security Management Perspective" focuses on strategic level, security considerations related to moving to the cloud. Chapter "An Overview of Cloud Forensics Strategy: Capabilities, Challenges and Opportunities" outlines a model for cloud forensics, which can be viewed as a strategic approach used by other stakeholders in the field, e.g., the court of law. Chapter "Business Intelligence Tools for Informed Decision-Making: An Overview" explains business intelligence and analytics concepts as a means to manage vast amounts of data, within complex business environments.

The objective of the book is to increase the awareness at all levels of the changing and enhanced technological environments we are living and working in, and how this technology is creating major opportunities, limitations and risks. The book provides a conceptual foundation, moving to a variety of different aspects of strategic engineering modelling approaches with the view of challenges not only faced by organisations but additional technological challenges we are consistently moving towards. Within this area we reflect upon the developments in and approaches to strategic engineering in a thematic and conceptual manner.

We hope that by introducing material on topics such as through-life sustainable systems, cloud computing, systems engineering, big data analytics systems modelling, we have been able to build knowledge and understanding for the reader; after reading this book the reader should be equipped with a greater appreciation and understanding concepts and the key alignment of strategic engineering within real-world case examples. There is only a limited amount which can be contained in each chapter; all of the chapter topics warrant a book in themselves. The focus is clearly on presenting a high-level view of relevant issues. We would further like to take this opportunity to thank the contributors for preparing their manuscripts on time and to an extremely high standard.

Leeds, UK

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Contents

Part I
Systems Lifecycle, Sustainability, Complexity, Safety and Security

Mathematical and Computational Modelling Frameworks for Integrated Sustainability Assessment (ISA)

Maryam Farsi, Amin Hosseinian-Far, Alireza Daneshkhah and Tabassom Sedighi

Abstract Sustaining and optimising complex systems are often challenging problems as such systems contain numerous variables that are interacting with each other in a nonlinear manner. Application of integrated sustainability principles in a complex system (e.g., the Earth's global climate, social organisations, Boeing's supply chain, automotive products and plants' operations, etc.) is also a challenging process. This is due to the interactions between numerous parameters such as economic, ecological, technological, environmental and social factors being required for the life assessment of such a system. Functionality and flexibility assessment of a complex system is a major factor for anticipating the systems' responses to changes and interruptions. This study outlines generic mathematical and computational approaches to solving the nonlinear dynamical behaviour of complex systems. The goal is to explain the modelling and simulation of system's responses experiencing interaction change or interruption (i.e., interactive disruption). Having this knowledge will allow the optimisation of systems' efficiency and would ultimately reduce the system's total costs. Although, many research works have studied integrated sustainability behaviour of complex systems, this study presents a generic mathematical and computational framework to explain the behaviour of the system following interactive changes and interruptions. Moreover, a dynamic adaptive response of the global

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system over time should be taken into account. This dynamic behaviour can capture the interactive behaviour of components and sub-systems within a complex global system. Such assessment would benefit many systems including information systems. Due to emergence and expansion of big data analytics and cloud computing systems, such life-cycle assessments can be considered as a strategic planning framework before implementation of such information systems.

1 Introduction

Sustainability can be defined as sustaining, preserving and enhancing some valuable or valued condition(s) over time in a dynamic system [12]. The sustainability science studies the complex relationship between nature and society in a global environment so-called global system. This complex interaction can occur between a broad range of sub-systems such as economic, ecological, technological, environmental and social notations [24, 35]. In the context of information systems, sustainability assessment is usually focused on the economy domain [33]. For instance, the interplay between human activities in a society and economy affects economic growth or decay, the standard of living, poverty, etc. Moreover, the interaction between human behaviour and ecological systems tends to focus on global warming, energy security, natural resources and biodiversity losses, etc. Finally, the interplay between humankind's actions, knowledge and activities and technological environment improve or regress technology, increase or decrease safety and has effects on the healthiness of people's daily lives. Meanwhile, Integrated Sustainability Assessment (ISA) applies sustainable principles to provide and support policies and regulations and incorporate decision-making in a global system across its life cycle. Therefore, ISA can be a solution-oriented discipline to evaluate the behaviour of a complex global system. The complete discipline integrates a broad range of knowledge and methodologies towards defining solutions. In this context, the development of a robust and integrated framework for sustainability assessment is of paramount importance.

Understanding the sustainability concept is clearly the basis for sustainability assessment. Sustainability or Sustainable development was first described by the Brundtland's report titled 'Our Common Future' published by the World Commission on Environment and Development. The paper argued that sustainable development means "development that fulfils the needs of the present without compromising the ability of future generations to meet their own needs. This contains two key concepts. (i) The concept of 'needs' in particular the necessary requirements of the world's poor, to which overriding priority should be given, and (ii) the idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future need" [13]. This argument tailed by several debates and discussions on how sustainability should be defined, interpreted and assessed [61]. Sustainability assessment can be described as a process to identify and evaluate the effects of possible initiatives on sustainability. The initiative can be a proposed or an existing policy, plan, programme, project, piece of legislation or a current practice or activity [63]. Developing transformative life cycle and system-oriented tools and methodologies both at national and international levels have been studied since late 1980s and earlier 1990s. Multiple factors and indicators can reflect the complexity of a global system's behaviour. This motivated efforts to combine indicators into integrated, quantitative measures of sustainability called Integrated Sustainability Assessment (ISA) [51].

In [5], Altieri investigated the critical issues which had an effect on productive and sustainable agriculture in Latin America using integrated pest management programs as case studies. He discussed that the attainment of such agriculture is dependent on new technological innovations, policy changes, and more socio-equitable economic schemes [5]. Furthermore, in [20] the concept of Triple Bottom Line (TBL) has been added to the accounting perception by John Elkington [20]. The TBL framework considers the interaction between three parts: social, environmental (or ecological) and economic in one global business system as illustrated in Fig. 1. Moreover, TBL introduced three dimensions commonly called the three Ps: People, Planet and Profit into the sustainability concept [21]. This new impression became a favourite subject in sustainability which requires consideration of economic, social and natural environmental parameters to characterise the valued conditions in sustainability [34]. Smith and McDonald [71] presented that agricultural sustainability assessment encompasses biophysical, economic and social factors. Therefore, they considered more parameters to assess the agricultural sustainability using multiple qualitative and quantitative indicators [71]. In the late 1990 s and early twentieth

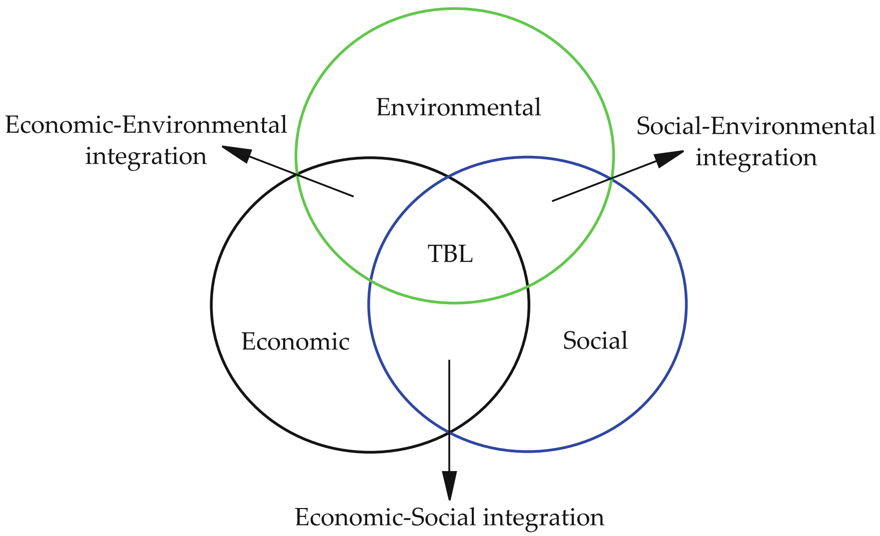

Fig. 1 The three pillars of sustainability or the three Ps: People, Planet and Profit; TBL is an integrated interaction between the environmental, economic and social dimension of global sustainability

century sustainability assessment has been developed by including the integrated sustainability science theory. In 1996, Rotmans and Asselt described integrated assessment as "integrated insights to decision makers" [65]. In this context, integration definition considers the combination of different parameters, functions, policies and regulations into a whole global system in an appropriate way that achieves a particular goal and purpose within the system. Integrated Sustainability Assessment (ISA) necessitates the following characteristics: (i) It should be conducted with explicit awareness of the global system; (ii) It should be directed by comprehensive aims, policies and regulations preferably explicitly articulated though initially less specifically; (iii) It usually requires stakeholder's involvement due to the significant influence of the policies and outcomes evaluation criteria on the direction of an integrated sustainability assessment; (iv) Sustainability assessment criteria are dynamic, time dependent and will change over time; (v) Integration is expensive since it necessitates a significant amount of time and different resources [12].

As mentioned earlier, assessment of integrated sustainability is a complex process due to the diversity of variables, parameters, formulations, policies and regulations in a global system. Sustainability assessment provides information for decision-makers to decide what action they should take or what policy they should apply within the system to make society more sustainable. The integrated assessment arises from Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA). However, SEA has been divided into economic and social approaches as well as the environmental aspect, which still reflects the Triple Bottom Line (TBL) approach to sustainability [29]. The overall aim of sustainability assessment is mainly to minimise unsustainability with respect to TBL objectives [11, 63]. Moreover, sustainability assessment can be conducted to evaluate a policy implementation into a system to inform, advise and update a management practice within the system. This study focusses on both mathematical and computational integrative methods within sustainability assessment. This multi-functionality and multiplicity of sustainability assessment terminologies and methodologies can be confusing. Therefore, this research study proposes a generic framework for the corresponding strengths of numerous approaches and methods which can be used by industrial ecologists and engineers and ecological and biophysical economists. This generic framework can also be used as starting point for many computer scientists and relevant industries for life-cycle assessments and applications of computing emerging technologies and systems such as big data analytics, systems set up, around cloud services and Internet of Things (IoT).

2 Integrated Sustainability Assessment (ISA)

This section discusses the triple pillars of sustainable development integration and describes the existing mathematical and computational methods concerning development of an integrated decision support system for sustainability assessment. In this context, the system is considered as a complex global system. As mentioned earlier, in a sustainable global system, the three pillars of sustainable development are Environmental, Economic (i.e., prosperity or profitability aspects) and Social. Initially, the characteristics and features of complexity in a system have been discussed by reviewing standard measures of complexity from relevant scientific literature. Then, in order to bring mathematical and computational flexibility and rigour to the issue, different statistical complexity measurements, and computational modelling features have been discussed.

A complex system is a system with numerous interdependencies in its structure. Such systems are sensitive to any small perturbations which may affect the initial conditions. In a complex system, the interactions between the independences and components are numerous. Therefore, the responses of the system to these perturbations and changes are not unique. Such behaviour is complex since the system can take multiple pathways to evolve. Moreover, the growth and development of a complex system may vary over time, and therefore this categorises such a system as a dynamic one. In this paper, the notion of complex dynamical system is denoted to a global system. A global system can be described as a System of Systems (SoS) which is composed of several sub-systems [33]. Analytically, the behaviour of such a complex dynamical system can be derived by employing differential equations or difference equations [77]. The key features and properties that can be associated with a global system are nonlinearity, feedback, spontaneous order, robustness and lack of central control, hierarchical organisation, numerosity and emergence, [50].

Although, nonlinearity is one of the features of a complex system, the behaviour of such system can also be linear where the corresponding parameters and objectives can be written as a linear sum of independent components. Meanwhile, linear studies can be used to understand the qualitative behaviour of general dynamical systems [36]. Analytically, this can be achieved by calculating the equilibrium points of the system and approximating it as a linear trend around each such point. Nonlinearity is often considered to be a vital characteristic of a complex system. The nonlinear system is a system that does not satisfy the superposition principle. The nonlinear behaviour of a global system becomes more complex regarding the diversity and variety of sub-systems' properties, conditions, and boundaries other than sub-systems variations. For instance, the complexity of living organism as a global system with numerous properties of being alive or dead other than a variety of its sub-systems and components (e.g., Human organisms composed of trillions of cells which are clustered into particular tissues and organs). Mathematically, for such global systems, typically, it is required to generate nonlinear differential equations to explain their dynamic behaviour.

Feedback is an important feature of a global system since the interaction between sub-systems are dynamic and are changing over time. Therefore, the behaviour of a nonlinear dynamic system extensively depends on the accuracy of the relations and interactions between its components. One of the typical examples of such systems in this context is the behaviour of a colony of ants that interact with each other. The quantitative approach to model such a complex behaviour can be defined by a nonlinear first-order differential equation, so-called System Dynamics (SD) which will be discussed later in this chapter. Since a complex dynamical system can be composed of a large number of elements, identifying the order of interaction between these elements are difficult and not clear. The spontaneous behaviour of orders is one of the most perplexing problems to define the behaviour of the complex systems on the feedback and information processes within the system over time. Moreover, the orders in a complex system can be robust in the system due to the scattered origin. Despite the sensitivity of a global system to any perturbation, orders are stable under such conditions. For example, consider a group of flying birds as a global system; they stay together, and the order of the pathways they take do not change, despite for instance any internal disruption such as the individual motion of the members or external disruption caused by the wind. Mathematically, robustness can be formulated in a computational language as the capability of a complex system to correct errors in its structure [68].

As mentioned earlier, a global complex dynamical system is composed of components and elements, so-called sub-systems. Such structures can resemble the structure of a hierarchical organisation. Subsequently, numerosity is an inherent property of a complex structure referring to the numerous number of sub-systems and parts in one global system. In a complex system, there may be different levels of organisations with individual properties and features. Emergence can arise from a robust order due to the complex interaction between these organisations and sub-systems within the global system. In system theory, emergence process between sub-systems is fundamental of integrative levels and complex systems [70].

Hitherto, different characteristics and properties of a global system have been explained briefly. Consequently, integrated assessment contributed to the sustainability science through developing a framework for different analytical and computational methodologies considering uncertainties, life-cycle thinking, policies, plans and regularities. In the following section, a different aspect of Integrated Sustainability Assessment (ISA) with regards to TBL is discussed, followed by introducing the related methodologies, models, tools and indicators. Moreover, ISA can be developed to define and evaluate the relationships between environmental, economic and social dimensions intended for optimising the interactive outcomes considering the TBL boundaries and constraints.

2.1 Environmental Sustainability Assessment

The environmental aspect of sustainability assessment is mainly viewed as ecological sustainability. The fundamental principles of environmental sustainability assessments focus on reducing the constructional embodied energy and CO_2 emissions; reducing the life cycle of atmospheric emissions (i.e., CO_2, NO_x, SO_x, CH_4, N_2O, etc.) and the waterborne emissions (i.e., COD, BOD, Total P, Total N, etc.) and limiting the requirement for water, fossil resources and natural gas [69]. Environmental sustainability assessments can provide indicators and indices as qualitative measurements to represent the environmental development in a defined system [35]. Indicators should be simple and transparent, measurable and quantifiable, sensitive to change and interruptions and time-dependent [58]. In particular, there are a number of environmental assessments developed by the Office for National Statistics (ONS). The UK's Office for National Statistics (ONS) is one of the largest independent national statistical institutes. One of the main tasks of ONS is to collect, develop and publish official statistics related to environment, economy, population, and society at national, regional and local levels [59]. According to the ONS, the headline 'environmental assessments' considers greenhouse gas emissions, natural resource use, wildlife: bird population indices and water use. Moreover, the corresponding supplementary measures are as follows: UK CO_2 emissions by sector, energy consumed in the UK from renewable sources, housing energy efficiency, waste, land use & development, origins of food consumed in the UK, river water quality, fish stocks, status of species & habitats and UK biodiversity impacts overseas [59].

The main and fundamental benchmark for evaluating the impact of environmental dimension on sustainability can be done by assessing the environmental performance of a global system using Environmental Life-Cycle Assessment (LCA). However, this assessment is not sufficient to understand the dynamic and interactive behaviour of environmental and ecological impacts. LCA is a simplified quantitative approach based on the traditional linear behaviour of complex systems. Despite the LCA's limitations and challenges in obtaining qualitative data, LCA can be still considered as the most comprehensive approach for environmental impact assessment [32]. The International Standards Organisation (ISO) is the institution that is responsible for establishing principles and guidelines for life-cycle assessment [76] called ISO 14040:2006– Principles and Framework [40] and ISO 14044:2006–Requirements and Guidelines [41] for LCA. According to the ISO standards, life-cycle assessment falls into two distinct classes based on its origin as Economic Input-Output based LCA (EIO) and Ecologically based LCA (Eco-LCA). Moreover, the corresponding LCA terms and expressions are defined as follows:

- Life cycle: "consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to final disposal".
- Life-cycle assessment (LCA): "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life-cycle".
- Life-cycle inventory analysis (LCI): "the assessment involving the compilation and quantification of inputs and outputs for a product throughout its lifecycle".
- Life-cycle impact assessment (LCIA): "the assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system throughout the lifecycle of the product".

Therefore, the life-cycle assessment is carried out in four distinct phases as illustrated in Fig. 2. These four phases are (i) Goal and scope definition, (ii) the Life-Cycle Inventory Analysis (LCI), (iii) the Life-Cycle Impact Assessment (LCIA) and (iv) the Life-Cycle Interpretation phase. Goal and scope phase focuses on identifying the aim of the LCA study and the corresponding objectives and applications with regards to the system boundaries, assumptions and constraints. Afterwards, in the inventory analysis phase, the essential data are collected to fulfil the objectives

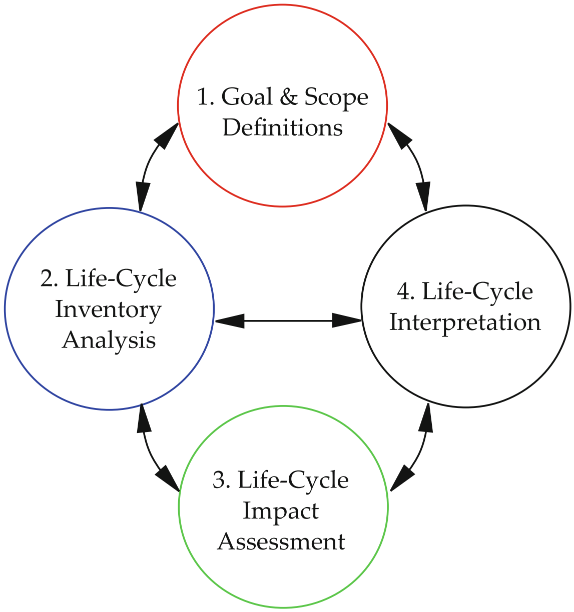

Fig. 2 Life-Cycle Assessment phases

of the LCA study. The data collection can be achieved by inventorying the input and output data from the studied system. Subsequently, the results from inventory analysis are transformed into the corresponding environmental impacts such as utilisation of natural resources, human health and safety, etc. in the impact assessment phase. The final phase of the LCA study is life-cycle interpretation. In this phase, the results of the inventory and impact assessments are evaluated in order to provide information for decision-makers which will ultimately help to develop essential policies and recommendations based on the goal and scope definition in the studied system. Recently, ISO published a general guideline on the implementation of ISO 14004 [39] which applies to any organisation with respect to their environmental principles, products and delivered services.

Considering different life-cycle assessment approaches; Economic Input-Output Life-Cycle Assessment (EIO-LCA) method evaluates the required raw materials and energy resources, estimates the environmental emissions, and assesses the economic activities in a system. EIO-LCA is one of the LCA techniques for life-cycle assessment study which is helpful for evaluating environmental impacts of a product or a process over its life cycle. This method has been invented and developed by Wassily Leontief in [53]. Economic Input-Output (EIO) theory introduces a mathematical modelling approach to systems life-cycle assessment and therefore can be beneficial to industry. It can be used for evaluating the financial transactions based on inputs and outputs within the sector. EIO model can be formulated as a matrix X_{ij} which represents the financial transaction between sectors i and j in a particular year. Therefore, using this method, the necessity of the input for an internal transaction in a sector can be indicated as (i.e.,: $X_{ij} \neq 0$ where $i = j$). Moreover, the direct, indirect and total effects of alterations to the economy can be identified using linear algebra techniques [53].

Consider matrix A_{ij} as the normalised output amounts for sector j, so that $A_{ij} = X_{ij}/x_j$. In addition, consider a vector of final demand, y_i, for the output from sector i. Therefore, the total output from sector i, x_i can be calculated as the summation of the output from sector j as a consumer and the total transaction between other sectors X_{ij}, thus

$$\begin{aligned} x_i &= y_i + \sum_j X_{ij} \\ &= y_i + \sum_j A_{ij} x_j, \end{aligned} \tag{1}$$

the vector notation of the Eq. 1 is thus:

$$x = y + Ax \quad \Rightarrow \quad x = (I - A)^{-1} y. \tag{2}$$

Material Flow Analysis (MFA) is an analytical method for quantifying stocks and flows of materials and entities within a system. MFA is capable of tracking the entities (e.g., materials, productions, etc.) and evaluating their utilisation in a system. Combining traditional economic input-output modelling approach with material flow analysis creates a mixed-unit input-output analysis technique to track and evaluate the economic transactions under changes in productions [31]. The other method to estimate the direct and indirect resource requirements of a system is the well-known Physical and Monetary Input-Output (PMIO) method which evaluates all the physical flows associated with the system economy [81].

In addition to the methodologies and techniques discussed, in order to assess the economic aspect of the life cycle, the Ecologically based Life-Cycle Assessment (Eco-LCA) method evaluates the role of ecosystem services in life-cycle assessment. Eco-LCA classifies resources into the following categories: (i) Renewable versus non-renewable, (ii) biotic versus abiotic, (iii) materials versus energy or (iv) regarding their originating ecosphere (lithosphere, biosphere, hydrosphere, atmosphere and other services). Eco-LCA is a physically based approach to assess the flows and interactions between considered resources in a system. For instance, Material Flow Analysis (MFA), Substance Flow Analysis (SFA) and Energy Flow Analysis (EFA) are some physical flow-based assessments for Eco-LCA of a system. Material flow analysis focuses on biophysical aspects of human activity with a view to reducing environment-related losses. Substance flow analysis is an analytical method to quantify flows of certain chemical elements in an ecosystem. However, energy flow analysis focuses on the flow of all types of energy such as exergy and emergy-based on the first law of thermodynamics.

2.2 Economic Sustainability Assessment

The second dimension of sustainability assessment is Economic Sustainability Assessment (ESA) which is focused on estimation of prosperity and profitability of a global system over its life cycle [30]. ESA can be generated to estimate the required economic growth, necessary for maintaining the sustainability of a system. In particular, the economic dimension of sustainable development in the UK can be measured by the following benchmarks: economic prosperity, long-term unemployment, poverty and knowledge and skills measure. Moreover, the supplementary measures are as follows: population demographics, debt, pension provision, physical infrastructure, research and development and environmental goods & services sector [59]. One example of the economic indicators for monitoring economic prosperity is called Gross Domestic Product (GDP), which represents the scale of economic activities within the country. This indicator is developed by the UK Office of National Statistics (ONC). Similarly, Domestic Material Consumption (DMC) is an important indicator to measure resource productivity in the context of Europe 2020 strategy [22]. DMC indicator relates to the gross domestic products which are developed by Statistical Office of the European Communities (Eurostat). Eurostat is the statistical office of the European Union and is responsible for providing statistics, accounts and indicators supporting the development, implementation and monitoring of the EUs environmental policies, strategies and initiatives [73]. Moreover, Net National Product (NNP) is another economic indicator which represents the monetary value of finished goods and services. NNP can be calculated as the value of GDP minus depreciation. In accountancy, depreciation refers to the amount of GDP required to purchase new goods to maintain existing. GDP and NNP are the two most frequently used benchmarks by decision-makers, are defined to measure and assess the overall human welfare [58].

Life-Cycle Cost Analysis (LCCA) is the most powerful benchmark for evaluating the economic impact of sustainability. LCCA is applied to evaluate the economic performance of a system over its entire life. The cost assessment considers the total cost including the initial cost, operating and service cost, maintenance cost, etc. Therefore, identifying activities and subsequently, the associated costs is the initial requirement for conducting the life-cycle assessment study. Although, the Environmental Life-Cycle Assessment (ELCA) methodologies where the focus was on the material, energy and resources flow, within the Life-Cycle Cost Assessment (LCCA) money flows would be the main focus. Furthermore, the Full Cost Environmental Accounting (FCEA) is another life-cycle costing analysis method. Both LCCA and FCEA approaches assess the environmental cost, and therefore they are appropriate methods for evaluating the economic impacts of sustainability. Within the context of information systems, this pillar of sustainability is the major context where sustainability and resilience of the system are assessed. Hosseinian-Far and Chang outlined the metrics required for assessing the sustainability of selected information systems. It is also argued that such economic sustainability assessment of information systems and the use of metrics is context dependent [33].

2.3 Social Sustainability Assessment

The third pillar of sustainability assessment is referred to as Social Sustainability Assessment (SSA). This assessment provides measures and subsequent guidelines required for identifying social impacts on sustainability assessment in a global system. In this context, a global system is composed of numerous entities. These entities can be organisations, individuals, shareholders, stakeholders, etc. In such a system these entities have an obligation to provide services and actions for the benefit of society as a global system. This responsibility is called Social Responsibility (SR). In another word, SR is a duty every entity has to perform so as to maintain a balance between the economic and the ecosystems [8]. According to the UK Office for National Statistics (ONS), the following measures are the social benchmarks of sustainable developments: healthy life expectancy, social capital, and social mobility in adulthood and housing provision. Furthermore, supplementary social indicators are as follows: avoidable mortality, obesity, lifestyles, infant health, air quality, noise and fuel poverty.

Social Life-Cycle Assessment (SLCA) is the third dimension of life-cycle sustainability assessment which assesses the social and sociological impact of an organisation, individuals, and products along the life cycle [25]. In addition, the Millennium Ecosystem Assessment (MEA) estimates the impact of ecosystem changes on human well-being by considering health and security, social relations, freedom, etc. [8]. These social aspects are gathered and developed by the Sustainable Consumption and Production (SCP) in order to generate and implement the corresponding policies and actions for public and private decision-makers. However, identifying and evaluating social aspects are challenging since some of the social performance data are not easily quantifiable [66]. These aspects can be categorised as human rights, working condition, health and safety, cultural heritage, education, etc. [10].

Regarding the society impacts on sustainability assessment, the Joint United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) develop knowledge and provide support in order to put life-cycle thinking into effective practices. This international life-cycle partnership is known as the Life-Cycle Initiative (LCI), established in 2002 [43]. SETAC is a worldwide and not for profit professional society that its main task is to support the development of principles and practices for support, improvement and management of sustainable environmental quality and ecosystem integrity [67]. Whereas, the UNEP as the leader of global environmental authority develops and implements the environmental dimension of sustainable development within the United Nations (UN) system and intends to support the global environment [10, 25].

Social assessment techniques and methodologies focus on improvement of social conditions since the main goal in SLCA is enhancing human well-being [9]. Human well-being can be evaluated through many indicators and terms. The most common ones are human development, standard of living and quality of life. For instance, Human Development Index (HDI) is an integrated indicator composed of life expectancy, education and income used by the United Nations Development