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ENGINEERING SUSTAINABLE COMPLEX SYSTEMS

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Abstract
Given the most competitive nature of global business environment, effective engineering innovation is a critical requirement for all levels of system lifecycle development. The society and community expectations have increased beyond environmental short term impacts to global long term sustainability approach. Sustainability and engineering competence skills are extremely important due to a general shortage of engineering talent and the need for mobility of highly trained professionals [1]. Engineering sustainable complex systems is extremely important in view of the general shortage of resources and talents. Engineers implement new technologies and processes to avoid the negative environmental, societal and economic impacts. Systems thinking help engineers and designers address sustainable development issues with a global focus using leadership and excellence. This paper introduces the Systems Engineering (SE) methodology for designing complex and more sustainable business and industrial solutions, with emphasis on engineering excellence and leadership as key drivers for business sustainability.
The considerable advancements achieved in complex systems engineering indicate that the adaptation of sustainable SE to business needs can lead to highly sophisticated yet widely useable collaborative applications, which will ensure the sustainability of limited resources such as energy and clean water. The SE design approach proves critical in maintaining skills needed in future capable workforce. Two factors emerged to have the greatest impact on the competitiveness and sustainability of complex systems and these were: improving skills and performance in engineering and design, and adopting SE and human systems integration (HSI) methodology to support sustainability in systems development. Additionally, this paper provides a case study for the application of SE and HSI methodology for engineering sustainable and complex systems.

Keywords
systems engineering, sustainability, human factors, human systems integration, complex systems.

Introduction

This paper discusses concepts of Systems Engineering (SE) with the focus on engineering sustainability, complexity and cost savings they offer. Users of complex systems have benefited from the growing interest of industrial and defense research in seeking automated and integrated systems, in addition to the application of technological innovation to improve competitiveness, increase system performance and reduce the total ownership cost (TOC). In this context, system testing, usability evaluation and sustainability of limited resources represent an essential task in the system development lifecycle to directly improve user experience and, consequently, the success in the market [2]. The research into SE and sustainability, presented in this paper, have also come to play an important role in complex systems design and development. For example, new engineering technologies provide novel and enhanced modes for human-system interaction to enhance the user experience and conduct effective testing and evaluation at the minimum cost, starting from the early stages of development.

For example, in conducting system testing and evaluation, researchers indicate that most systems have an inherent risk which can be estimated using the reliability engineering and performance and safety evaluation methods or based on the calculations using the failure modes and effects analysis (FEMA) or the mean time between failures (MTBF). Research in human factors engineering and human systems integration (HSI) confirms that the human component is the most variable component due to its association with nonlinearity, complexity, dynamic behavior and properties such as fatigue, mood, and emotions along with a large set of biological factors. However, human component in any system provides the strength and integrity to all systems due to its flexibility and adaptability to all environments including extreme and stressful working conditions.

The human component in the system serves as the "saviors" and control mechanism preventing chaotic behaviour. Thus future research builds on the growing body knowledge in human factors and ergonomics (HF&E) along with many other disciplines to study the human weaknesses and strengths in relation to sustainability of complex systems and focus on the dynamic system behaviour and properties to maximize systems and process efficiency and effectiveness. This paper presents the SE methodology for sustainable development of complex systems, methodologies presented in this paper proved effective to streamline the evaluation and testing of complex systems and to demonstrate their applications.

Sustainable development

While planning for the future, engineers and system designers provide end-to-end solutions not just quick deliverables seeking compliance with environmental and social obligations. System engineers implement new technologies and processes to avoid the negative environmental, societal and economic impacts. This paper discusses a "system of systems approach" to design complex and more sustainable business solutions.

Systems thinking help engineers and designers address sustainable development issues with a global focus using leadership and excellence. For example, engineers should consider the following questions when designing systems in order to maintain ethical and sustainable development responsibility:

- The system or product can be manufactured or developed without compromising safety, environment and workforce health.
- Respond to leadership, economical, timeline and other challenges.
- Identify the skill-set, tools, and characteristics needed to deliver more sustainable and engineered outcomes.

The global society formally included the relevance of sustainability in 1992 during a convention held in Poznan, Poland for the United Nations Framework Convention on Climate Change (UNCFCC) [3]. Given that global population is increasing at the rate of approximately more than 1.5 percent per year [4], sustainable development has become a key concept and global challenge facing growing population needs, economic development and climate change in the 21st century. The World Commission on Environment and Development's (WECD) defined sustainable development as the "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". In this definition, "*sustainable development*" can be delivered by the balanced approach between the user needs and system requirements to improve the quality and preserve resources.

The National Academy of Engineering (Engineer of 2020: Visions of Engineering in the New Century) [5], stressed on the importance of engineering leadership and innovation: "...In the past those engineers who mastered the principles of business and management were rewarded with leadership roles. This will be no different in the future. However, with the growing interdependence between technology and the economic and social foundations of modern society, there will be an increasing number of opportunities for engineers to exercise their potential as leaders, not only in business but also in the nonprofit and government sectors. In preparation for this opportunity, engineers must understand the principles of leadership and be able to practice them in growing proportions as their careers advance" [5].

Engineering leadership can be supported by the structured process of analyzing system requirements versus manpower and workforce skills and characteristics in the organization to determine suitable training and skill sets engineers need before they are able to contribute to system development. Table 1 shows a list of selected key skills required by engineers to achieve effective sustainable development [6].

Sustainable development and technological leadership can be achieved through Systems Engineering (SE) concepts and methodology, which support engineering global leadership and innovation, and recognizes that any development effort implemented in isolation will produce only limited results. For example, implementing new service functions or procedure without appropriate training or coaching will not produce improvement. According to Wilson Learning [7], Human Performance Improvement (HPI) is a process and creative approach to training and coaching that acknowledges the critical role of tools, processes measurement, and management support which will enhance and extend the impact of learning through improved knowledge, skills and abilities (see Fig. 1).

Table 1
Key skills required by engineers (after Ahram et al. [8]).

–	An understanding of basic science principles
–	Application of the principles of science to the solution of engineering problems
–	Applying computer applications skills
–	Recognizing the systems, components and processes of a technological system
–	Developing and following a plan for the solution of a design problem
–	Understanding the properties of different materials
–	Selecting materials and processes necessary for developing a solution to engineering problems
–	Carrying out prototype development and testing
–	Applying critical and logical thinking skills
–	Explaining the impact of business on engineering
–	Solving problems using engineering tools and resources
–	Applying engineering graphics skills
–	Using mathematics in the context of engineering design
–	Applying the principles of mathematics to the solution of engineering problems
–	Developing vocabulary and reading comprehension skills
–	Applying technical, writing, and verbal skills to the communication of engineering design

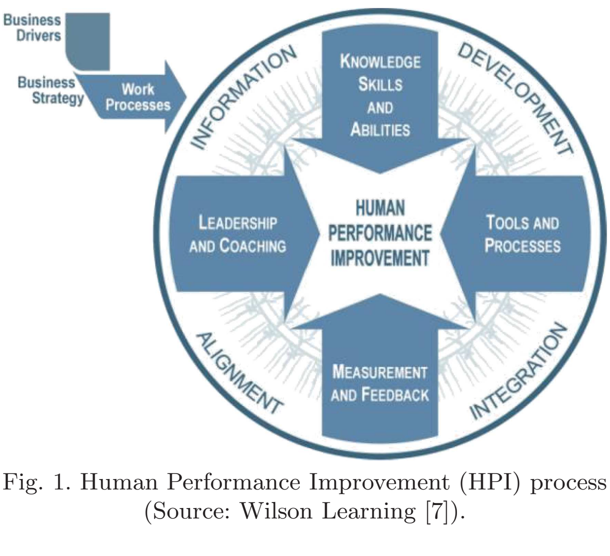

Fig. 1. Human Performance Improvement (HPI) process (Source: Wilson Learning [7]).

There are three elements to workforce leadership and innovation that are critical to creating best results [7]:

1. **Integrated technology solutions**: supporting the performance improvement elements necessary to address current challenges and accomplish the leadership strategy, this includes;
   - Ensuring management support and that they are prepared to coach the application of the skills;
   - Developing learning components to deliver the knowledge, skills, and abilities;
   - Providing organizations with the ability to track the impact of the learning on performance (e.g. business performances and analytics);
   - Developing work tools and process to support the use of the learning.
2. **Requirements understanding**: Making effective decisions about what skills to focus on and determining how to integrate systems and align all key components.
3. **Establishing** a business case.

Systems engineering

A system is defined by the International Council on Systems Engineering (INCOSE), as "an artifact created by humans consisting of components that pursue a common goal unattainable by each of the single elements". The engineering part of systems engineering represents the practice of employing tools and structured approaches to develop a product. Putting these two words together describes the SE practice of defining and documenting requirements for a product or process, preparing or choosing amongst design alternatives, assuring requirements have been met, and finally deploying, maintaining and disposing the system [8]. According to Ahram et al. [8] "The SE process is iterative, while employing optimization and streamlining, the various elements to ensure that cost, schedule, and operational requirements are met". Osborne et al. [9] describe the "Vee" model as a model relating systems engineering to the project cycle (see Fig. 2). The left side of the "Vee" model describes decomposition and definition activities; the center base represents the complete specification of system components, while the right side describes the quantitative verification activities assuring that requirements were met. As SE practices unfold, problems inherently develop. These challenges are addressed using the systematic approach integral to SE practices and, once sufficiently addressed as defined by the agreed-upon requirements, the process moves on to the next phase and next problem" [9].

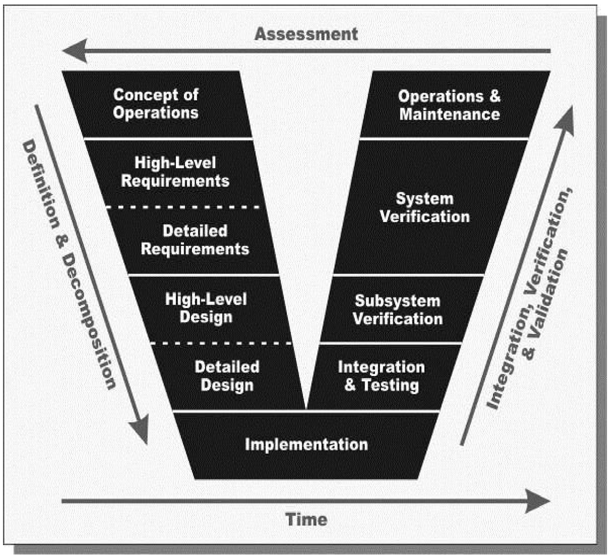

Fig. 2. Systems Engineering Vee Model (Osborne et al. [9]).

With hardware and software growing complexity, new functionalities are created, and overall system complexity increases accordingly. The sustainable approach in SE enables better management of systems complexity. According to Ahram et al. [8] the systems engineering practice affords a formal design approach that attempts to cover all aspects of design. This includes a robust risk management portion that, given good requirements, will yield a safe design. Safety is not the only benefit of following this approach, past performance on projects and previous research in systems engineering indicated that there is a positive correlation between utilizing formal systems engineering practices and the degree of success in an engineering undertaking, especially in the economic return on investment (ROI) [9–11].

Approach to sustainable development in systems engineering

Given today's economy, government and private business spending mandates a controlled spending with the focus on core processes especially when associated with the highest return on investment (ROI) and optimized total ownership cost (TOC). The application of SE process requires the implementation of a comprehensive design approach in order to achieve sustainability objectives and cost savings. Research by Ahram et al. [11] and Ahram and Karwowski [12] confirms the positive correlation between adopting a standard SE strategy, HSI practice and overall project sustainability with respect to resources and attainment of manpower skills, especially with respect to achieving project objectives with an acceptable TOC and ROI without compromising safety.

Engineers always have the strategic and leadership role in developing and maintaining sustainable solutions and outcomes. For engineers, a systems approach is considered as a strategic role for the development project, starting from the early concept design stage and across all other stages of product lifecycle development. It is important to plan for sustainable decision-making early in the development lifecycle to achieve sustainable outcomes [12]. The challenges facing global community, such as water, food and energy shortages, global warming and climate changes and environmental and soil degradation, are overwhelming. Engineers can make a difference as professionals in their own workplace by designing ingenious and innovative systems and adopting a system-of-systems approach.

According to Karwowski and Ahram [1], SE methodology utilizes a framework to control the complexity and the dynamic nature of systems. According to Guillerm, Demmou, and Sadou [13], SE process utilizes the following sequence of formal components "Processes → Methods → Tools". Starting with a structured process; design must be based on a formal design heuristics or well developed standards similar to EIA-632 [14]. The best practices are utilized from previous programs, while tools are based on methods used to convert requirements, concepts and conceptual ideas to detailed design. The objectives of SE process are to translate user requirements into solid engineering and technical specifications which will guide system and product design. Systems testing and evaluation must be considered during early design phases especially requirements gathering. Testing and evaluation verify that the system meets desired specifications and predict unanticipated safety consequences. Thus safety requirements act as constraint during system design phase, for example, safety may require fall protection or may limit shift duration to protect from fatigue, stress or sleep deprivation.

According to Ahram, Karwowski and Amaba [15] "The contemporary SE process is an iterative, hierarchical, top down decomposition of system requirements" [16, 17]. The hierarchical decomposition includes Functional Analysis, Allocation, and Synthesis. The iterative process begins with system-level decomposition and then proceeds through the functional subsystem level, all the way to the assembly and program level. The activities of functional analysis, requirements allocation, and synthesis will be completed before proceeding to the next lower level.

Modeling SE process activity is performed using Systems Modeling Language (SysML). SysML is a "general-purpose visual modeling language for specifying, analyzing, designing, and verifying complex systems which may include hardware, software, information, personnel, procedures, and facilities" (http://www.omgsysml.org) [18]. SysML provides visual semantic representations for modeling system requirements, behavior, structure, and parametrics, which is used to integrate with other engineering analysis models [19]. SE teams along with system designers are responsible for verifying that the developed systems meet all requirements defined in the system specification documents. The following procedures outline the relevant steps in the SE process [17]:

- Requirements analysis,
- Functional analysis,
- Performance and functionality
- Design Synthesis
- Documentation
- Specifications,
- Specialty engineering functions
- Requirements verification.

Systems modeling language

SysML is an extended version of the Unified Modeling Language (UML), created by the Object Management Group (OMG), and utilizes the capabilities of the graphical tool for modeling all types of systems. SysML has been implemented to system testing and evaluation because it integrates and simulates methods and processes in risk management including safety engineering. SysML provides added benefits for managing complexity and support traceability, the structure of SysML supports risk management in an applied setup, especially during the systems development lifecycle (SDLC) process. The overall objective of this paper is to demonstrate how SE and HSI supports managing complexity and improve the integration of human elements with user requirements, which offer a measurable and applicable area for mitigating risks and to conduct testing and evaluation.

SysML is based on representing systems using several types of diagrams as shown in Fig. 3. The basic components of SysML are "blocks" which are connected to define system structure and organization.

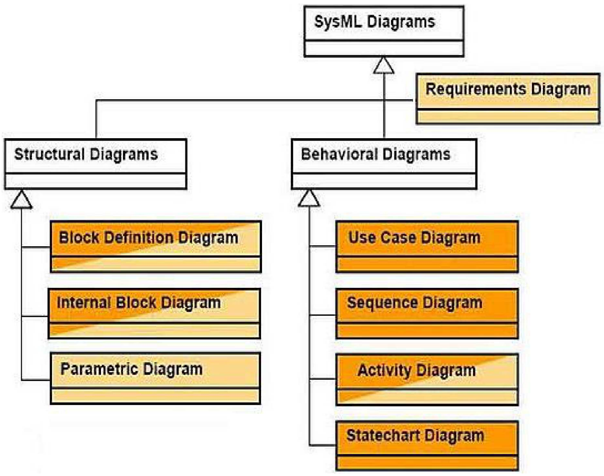

Fig. 3. Structure of Diagrams in SysML (Adapted from OMG SysML Website [18]).

SysML drives requirements by the logical integration of diagrams to visualize the user and functional [13] such as Block diagram (internal/external), sequence diagram, constraints (Parametric diagram), behavior (activity diagram, State chart), requirements (Use case diagram, Requirements diagram). SysML provides system behavior and structure using the following key diagrams [20]:

- Parametric diagrams – embed mathematical or algorithmic constraints against system properties.
- Sequence diagrams – visualize the flow of control and responsibilities with various system components.
- State machine diagrams – To model and simulate the behaviour and help developers and designers evaluate and test system states.
- Activity diagrams – provide sequences, inputs, outputs, and situations that govern various system behaviors.

SysML has been applied for conducting reliability analysis for complex systems. For example, David, Idasiak, and Kratz [21] demonstrated the application of SysML to conduct failure mode effects analysis (FMEA) and reliability analysis of automatic complex systems. Many challenges in conducting reliability analysis have been addressed by implementing following steps:

1. Quantification and extensive analysis of functional and dysfunctional behavior.
2. Integrating functional aspects employing formal language.
3. Applying the deduction and analysis methodology to investigate and identify of the impacted requirements.

A cited benefit of SysML is that it supports the functionality as a platform for performing system wide evaluation and supports requirements traceability, which is critical for evaluating safety and hazard analyses. Due to the exponential systems complexity, a common traceability technique used by systems investigators is slicing, which was developed to manage complex software by sliding it to chunks and distributing development and testing across various development team members. By employing slicing techniques in systems testing and evaluation, several activities can be investigated in parallel using SysML.

Engineering sustainable complex systems

According to Karwowski [22], the overarching problems of complex systems is supporting environment and resources used to generate low cost energy and steady source of clean water supply, and maintain security for the entire human population. It can be proposed that the main purpose of sustainability is to "optimize the beneficial affordances of the environment in order to ensure control of such environment by the society" [22]. Furthermore, sustainable approach for design of complex systems refers to "the design and management of affordances provided by the environment that are compatible with human social needs, abilities and requirements for sustainability and, the design and management of affordances that are compatible with social needs and requirements for sustainability" [22]. Fiskel [23] divided "environmental" performance indicators of sustainability into five different categories: "material consumption, energy consumption, local impacts, regional impacts, and global impacts" (see Table 2). On the other hand, the "societal indicators" of sustainability have been divided into six categories "quality of life; peace of mind; illness and disease reduction; safety improvements; and health and wellness" (see Table 3).

Table 2
Environmental sustainability performance indicators (after Fiskel [23]).

Material consumption	Product and packaging volume
	Useful product lifetime
	Hazardous materials used; eco-efficiency
Energy consumption	Energy Lifecycle
	Power use in operations
Local impacts	Product recyclability
	Runoff to surface water
Regional and global impacts	Smog creation, acid rain precursors
	Biodiversity reduction
Global impacts	Global warming emissions; zone depletion

Table 3
Societal indicators of business sustainability (after Fiskel [24]).

Quality of life	Breadth of product or service availability
	Employee satisfaction
Peace of mind	Perceived risk and community trust
Illness & disease reduction	Illnesses avoidance, mortality reduction
Safety improvements	Lost-time, injuries
	Number of incidents
Health and wellness	Nutritional, value provided
	Substance costs

One of the greatest challenges in the 21st century is to develop new objectives based on sustainable complex systems philosophy and design that advocates the systematic use of human factors and ergonomics (HF/E) and human systems integration (HSI) knowledge to achieve "compatibility" in the design of "environmentally", "economically" and "socially" sustainable systems of people and technology [22, 24–26]. The field of HSI focuses on integrating both human capabilities and limitations into design and development of systems and products.

Human-systems integration

Human factors professionals seek to evaluate the integration of manpower and workforce requirements with respect to the limitations and strengths to ensure effective system design. The increase in operators' workload is a direct result from change of job demands and the added volume and complexity of the information, additional labour constraints which may also reduce skilled labour availability. Testing and evaluation efforts focus on maximizing performance through improvement of system integration and safety to prevent fatigue, stress by balancing the introduction of new technology with workload requirements and in order to minimize TOC [15]. A study by the Government Accountability Office (GAO), examining 95 military projects worth \$1.6 trillion, reported projected cost overruns totaling \$295 billion (40%), and an average delay of 21 months in project schedules" [24, 25]. In summary HSI and SE efforts have resulted in saving billions in projects budget and prevented fatal accidents.

Given the importance of testing and evaluation to the SDLC process; designers invest in developing use case scenarios and studies to help identify safety concerns and support in proactive measures to prevent errors or accidents. The scenario selected for testing and evaluation reflect the criticality of mission success, following are key important issues to investigate when designing complex systems:

- Triggers for stress and fatigue.
- Critical decisions associated with manpower and skill management.
- Conditions associated with fatigue and excessive workload.
- Conditions that generates extreme hazards?

Complex systems must have the functionality to assign human operators to supervise, intervene or stop operation when necessary. Sheridan [26–28] indicated that the supervisory role and function is assigned according to automation tasks below:

- Development of heuristics and features to improve performance.
- Support the operator controls system states.
- Supervise task execution.
- Monitor system state for problematic conditions.
- Predict and represent the system behaviour and goals.

Engineering sustainable complex systems with SysML

Modeling sustainable complex systems using SysML includes the process of identifying both behaviour and structure, for example in SysML taxonomy, the modeling approach integrates manpower performance, skill and abilities with task requirements and functional analysis.

According to Ahram, Karwowski and Amaba [15] "SE concepts and principles are an integral part of the contemporary engineered world [16], such concepts are also used to create smarter consumer systems, protect human health, enable travel over great distances, and allow for instant and ubiquitous communication. These principles are also used to build energy efficient houses and transportation solutions, design workplaces, develop an infrastructure that society relies upon for smarter cities" [29, 30]. The SE principles are used to make complex systems and services cheaper, more functional, and get them to the market faster. Systems engineers apply and integrate concepts and rules derived from math and science to create and apply such principles [31].

An example of this model is the logistics providers, where the complex technology of package delivery is embedded in service systems computers that schedule and route the delivery of packages. The delivery personnel contribute to critical components of both delivery and pickup needed for satisfying user needs, this approach contributes to sustainable business processes [32].

Case study

The fundamental principle of the sustainable system development is to give novice designers a challenge to develop creative and new solutions and to support critical thinking by applying problem solving skills [32, 33]. Development of a conceptual system or business product model determines whether "the concepts about how the system should behave will be perceived by the end-user in the manner intended". The framework provided by Norman [34] (see Fig. 4) illustrates the relationship between "the design of a conceptual model and the end user understanding of product usage.

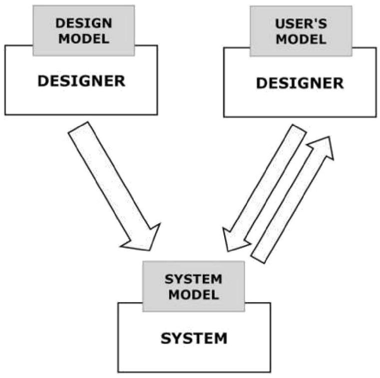

Fig. 4. Modeling the relationship between the conceptual model and the end user understanding of product and system usage (Preece et al. [35]).

In Fig. 4, there are three interacting components: the designer, the end-user, and the system". Preece et al. [35] indicated that behind each of these are three interlinking conceptual models [35]:

- The design model – designer's impression of how the system should work.
- The system component – how the system actually works.
- The user's model – the end – user's understanding of how the system works.

Systems engineering practitioners and human factors experts have realized the limitations and coined the term "Lessons Learned". Currently there are few applications to facilitate sustainable development with respect to requirements allocation. One of the commonly cited applications that support a full HSI and SE within a systems engineering process is DOORS^{TM} by IBM Rational Systems Engineering group for "Dynamic Object Oriented Requirements System" specifically to track requirements for product or software design. Since the requirements process has many shared elements to knowledge management, IBM DOORS facilitates requirements entry, organization into hierarchies, and display. Figure 5 shows a typical DOORS session. "Requirements" are shown in the left panel in hierarchical order and "detail views" are shown on the right.

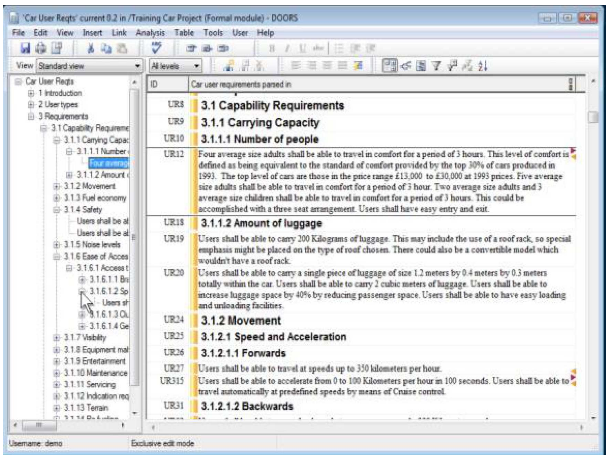

Fig. 5. IBM DOORS platform screenshot for car design requirements [2].

A comprehensive system or business process modeling framework facilitates the design of agile and sustainable business processes by capturing the core business knowledge into reusable modules and components [36]. In Fig. 6, "system development" is connected to "business maps and strategy ontologies" to aid in decision making and process improvement.

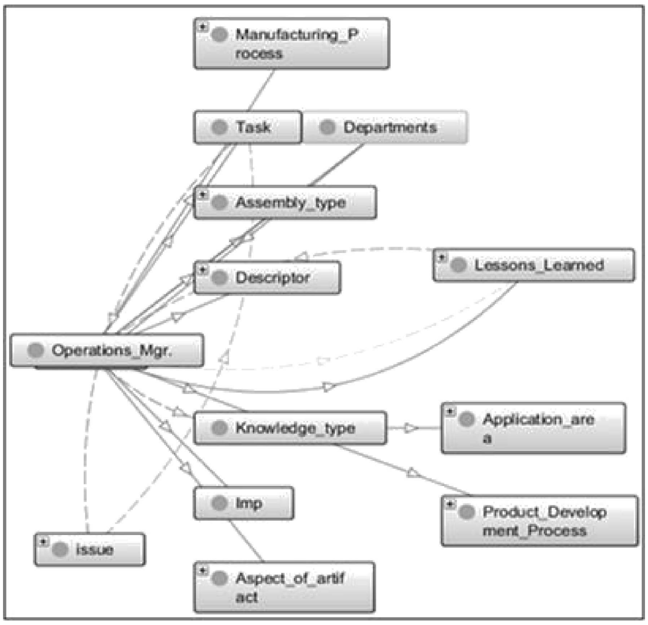

Fig. 6. Business model decision support structure based on SE methodology to support sustainable product lifecycle development (Adapted from original work by Karwowski and Ahram [37].

According to Ahram et al. [15] "This process is supported by the understanding of business roles through a business functions ontology that establishes process frameworks and architecture. These components can be seen as a complement to the traditional agile design engineering process" (see Fig. 6). A widely used SE support platform is CATIA or "Computer Aided Three Dimensional Interactive Application, a stand-alone program made by Dassault Systems and distributed by IBM, is an integrated suite of Computer Aided Design (CAD), Computer Aided Engineering (CAE), and Computer Aided Manufacturing (CAM) applications for digital product definition and simulation".

Figures 7 and 8 depicts a CATIA session for designing modern car safety system with passenger position prediction based on human factors engineering and ergonomics guidelines as discussed in the Handbook of Human Factors and Ergonomics Standards and Guidelines [38].

Fig. 7. CATIA SE session with car model design (Adapted from [39]).

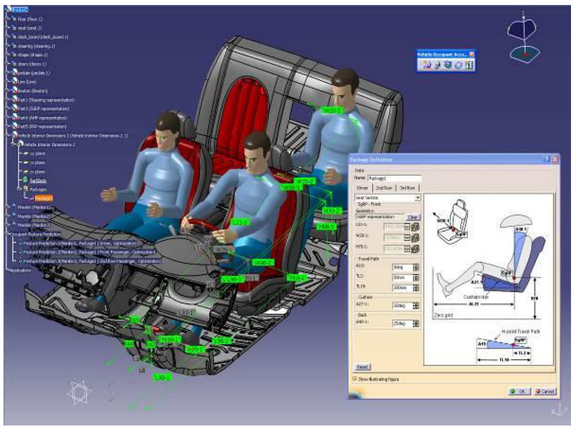

Fig. 8. CATIA session for designing modern car safety system with position prediction based on human factors engineering and ergonomics guidelines (Adapted from [40]).

CATIA allows manufacturers and designers to simulate various stages of design processes, from the planning all the way to detailed design, analysis, testing, assembly and maintenance. CATIA is primarily used by the automotive and aerospace industries for automobile and aircraft product and tooling design, it is well known that CATIA have been used by Boeing to design massive airplanes, and by NASA to help design the Space Shuttle. For example the new Falcon 5X systems project by Dassault Falcon [40].

Ultimately, organizations are responsible for employing a process or a set of processes for human factors knowledge creation, implementation, and utilization. With proper systems engineering practices in place, duplication of effort is minimized or eliminated, and the system design cycle is streamlined.

Conclusions

Having a strong infrastructure changes how nations innovate and prosper. Given the urgency of the situation, societies have to reuse, modify and apply best practices and technology solutions to accelerate the ability to solve sustainability issues such as the energy famine on the horizon. History calls on an effective and battle tested systems engineering discipline that has supported putting people on the moon, space exploration, medical devices, airplanes, cellular telephones, nuclear reactors, and defense systems.

This paper introduces an approach based on systems engineering methodology to support sustainable development, and demonstrates the contribution of systems engineering principles for the design and development of complex systems. While a large number of disciplines and research fields must be integrated towards the development of sustainable intelligent systems and products, considerable advancements achieved in these fields in recent years indicate that the adaptation of these results can lead to highly intelligent, sustainable and widely useable systems, products and services.

Additionally, this paper provides a motivation and quest for sustainable SE and HF/E approach in business modeling, complex systems design, skill development process and engineering leadership. The society and community expectations have increased beyond short term impacts to global long term sustainability goals. Engineering sustainable complex systems is extremely important in view of the general shortage of resources and talents. Engineers implement new technologies and processes to avoid the negative environmental, societal and economic impacts. The SE and HF/E disciplines will be well-positioned to facilitate the highest quality of life for all citizens by developing a consistent and verified approach to design universally usable and human-adaptable complex systems and technologies.

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