Incorporating Safety into Engineering Teams and the Design Process – A Teaching Module

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***Abstract*—Safety is the highest priority consideration for engineering education, and is particularly important in teamwork. Incorporating safety into engineering teams and the design process is the focus of this paper. The introduction to safety in engineering design and teams, safety documentation, rules and culture in design and teams, safety control and management schemes, some emerging trends in engineering design, teams and safety, and finally case studies are presented.**

***Index Terms*—safety, engineering teams, design process, teaching module**

I. Introduction

Health and safety are critical for engineers and engineering fields. Taking mechatronics engineering education as an example, many questions arise relating to safety. For example, what if the electrical power is not stable when designing and developing a robotic system for object searching? What if one team member makes a hidden mistake about which others do not know? What if there are sparks from a circuit? How to avoid or address such issues is the focus of this teaching module.

There are numerous resources dealing with health and safety in engineering fields. Available resources include books resources [1]-[6], organization-based health and safety materials posted on organization websites [7]-[9], particular safety and health subjects resources generated by safety-related organizations and agencies [10]-[18], and conference proceedings [19], [20]. The authors here just listed some of them since there are so many. For example in [20], an overview of an engineering teaching module on robotics safety was presented, different types of industrial robots, types and sources of robotics hazards, robot safety requirements, robot safeguards, and robot safety standards are all presented. This paper will mainly focus on the incorporating safety into engineering teams and the design process. To the best of the authors' knowledge, this will be the first paper that considers incorporating safety into engineering teams and the design process. This article is based on a health and safety module developed earlier by the authors for Minerva Canada.

The organization of the teaching module is expected to be as follows, in order to effectively incorporate safety into engineering teams and the design process: introduction and emphasis of the necessity and importance of safety in engineering design and team work are presented in Section II, Section III describes some documents on safety rules. The culture of safety will also be introduced to help explain the background of these rules. The concepts of management of change (MOC) and fostering a safety culture, both of which rely on the ability of teams and the people who form them to be able to work together, are presented in Section IV. Emerging trends in engineering design, teams and safety are discussed in Section V; Section VI presented two case studies of safety aspects relating to design and control of engineering systems to convey the ideas and importance of professional safety management in a team, and finally a task assignment for safe cooperation to individuals in a team involved in an engineering design process covering aspects of mechanical and electrical engineering are provided in Section VII.

II. Introduction to Safety in Engineering Design and Teams

A. Engineering Design and Safety

Improper design can lead to unexpected consequences in engineering. Sometimes such consequences involve safety risks, some of which result in safety incidents. Consequences can be as severe as death. Removing safety risks to ensure worker and public safety is a key component of engineering design and a responsibility of engineers and engineering teams. These statements embody the focus of this module, which is on understanding and mitigating the health and safety risks in engineering design and engineering teams.

Some examples of consequences of inadequate consideration of safety in engineering design are listed as follows: power plant fires, pipe explosions, bridge collapse, sparks from a circuit, design flaw in nuclear power plants, space shuttle Challenger disaster, oil spills,

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pipeline ruptures, and radioactive discharges, etc. Taking the design flaw in nuclear power plants and space shuttle Challenger disaster as two examples. For the Fukushima incident, the Tokyo Electric Power Company used two different designs for its six nuclear reactors at Fukushima Daiichi. When the tsunami hit, cooling system at reactors Nos 1 through 4 failed because critical backup generators and electrical switching equipment were housed in lightly protected turbine buildings that were swamped with seawater. Reactor No. 6 kept power because key equipment was located in the heavily fortified reactor building and a backup generator in a building next door kept running. For the space shuttle Challenger disaster, the space shuttle system was not made in a way to survive a failure of the solid rocket boosters. If the boosters do not work correctly after ignition, there are not any restorative measures that can be resorted to, i.e. there is no way to set apart an Orbiter from thrusting boosters safely and no way for crew members to get away from the vehicle in the first-stage takeoff.

Incorporating safety into engineering teams and the engineering design process is vital for protecting workers, the community and the people who live and work within it, emergency responders, etc., it is also vital for avoiding significant financial costs from safety incidents for businesses and communities, and attaining financial benefits in organizations associated with good health and safety practices, and protecting the conditions of the environment, in both the short and long terms, including the protection of ecosystems and the people, animals and other living entities within them.

B. Engineering Teams and Design

When designing a complex device or system, e.g., automobiles, aircraft, computers and manufacturing plants, many engineering experts from different areas come together in the design process. These experts need to cooperate, to consider each other's requirements and, often, to compromise regarding facets of engineering designs. Teams have meetings regularly throughout the design process to discuss different engineers' requirements and preferences, so that the whole team achieves the best design solution. For example when the material design team chooses a certain material from their perspective of merit, sometimes this will cause safety hazards in the mechanical structure the material is used in. For example, for the design of a space robot by NASA, various kinds of engineers comprise the team tasked with designing a complete robotic system. Each engineering group may have its specific subtasks. Robotic structural engineers, for instance, consider the requirements specified by robot control engineers so that the robot achieves optimum control performance.

C. Engineering Design Process and Safety

The engineering design process involves many steps, from problem statement and concept development to the final product or process. Safety must be considered throughout the engineering design cycle to ensure all areas of risk are addressed at every stage of the process. One way to illustrate the engineering design process is the engineering circle. Each of the steps in the engineering circle is now described.

Step 1: Problem statement. For example, existing safety issues with a current design or technology need to be identified. Here, one needs to determine the potential safety issues that exist within the system by resorting to current engineering methods.

Step 2: Requirements and constraints. The current design constraints and the requirements to fulfill the objective need to be understood. After one determines potential safety issues, the next step is to ascertain the requirements or final goals one is expected to achieve and relevant constraints that limit options.

Step 3: Uncertainty minimization. All available information is collected to reduce uncertainties in the design to a minimum. This step aims to minimize uncertainties that exist within the system or process. Although ideally uncertainties should be considered, they are sometimes ignored for the ease of analysis.

Step 4: Concept formulation. Mathematics and other methods are used to model the current design process. Concept formulation in engineering sometimes can be thought of as problem modelling. One needs to formulate the general and sometimes vague problem into a mathematical model to provide understanding and facilitate subsequent analysis.

Step 5: Design analysis. Engineering tools, like finite element analysis (FEA), are utilized to conduct analyses of potential hazards. After modelling, commercial engineering tools can be used to help identify hazards within the model. This step is usually called design analysis.

Step 6: Alternatives. Further investigations are carried out to seek any other alternatives to the current design. This step is optional. One can use mathematical analysis instead of engineering tools to analyze hazards within the model.

Step 7: Evaluation. Computer software is used to evaluate the current system or process. For example in engineering, Matlab software is often employed to help evaluate a system or process.

Step 8: Optimization. Computer software is used to optimize the current system or process and to improve it. Similarly in engineering, Matlab is often employed in system or process optimization.

Step 9: Recommendation. The optimization results from the prior step are used to develop recommendations for actions. The optimal solution can be recommended as an option for engineers or managers, or alternatives can be presented and recommended.

Step 10: Implementation. The recommended actions are implemented to improve the current design to make the operation and field work consistent with safe operating practices. In most instances, the design is executed following the recommendations.

III. Safety Documentation, Rules and Culture in Design and Teams

Standards are publications that establish accepted practises, technical requirements and terminologies. By using standards, organizations can ensure products and services are consistent, safe and effective.

A. Safety Standards and Codes

There are four types of standards that cover a broad range of requirements for products and services: performance, prescriptive, design, and management. For the performance, it makes sure that a product fulfills a prescribed test (e.g. strength requirements); for the prescriptive, it identifies product characteristics (e.g. dimensions of material); for the design, it sets out the specific design or technical characteristics of a product; for the management, it sets out requirements for the processes and procedures (e.g. environmental management systems).

To be considered valid and meaningful, standards must have the following traits: first of all, their development must be overseen by a recognized organization or authority, secondly, the development process has to be disclose to input from all interested parties, thirdly, the resulting standards have to be properly documented and publicly available, and lastly, a method must be available for tracking and proving that firms are following the standards.

Codes can include codes of practice, conduct, non-regulatory agreements, voluntary initiatives, and guidelines. Codes can cover a wide a range of activities, for example, labour standards, advertising, environmental protection, human rights, and public standards of decency.

B. Safety Culture and Its Impact on Teams

A safety culture relates to the ways in which safety is run within the workplace, and indicates the beliefs, attitudes, values and perceptions that employees share in relation to safety. A safety culture affects health and safety, as well as many other aspects of performance. Here, the London 2012 Olympic project is used as an example. Instilling a good safety culture made this project and its design a success.

Safety culture example – London 2012 Olympic project

The components that furnish the progress of the safety culture on the Olympic site include the following: first of all, the tactical role of the Olympic Delivery Authority (ODA) among the site, with safety being regarded as more important and blended in the firms involved from the outset through standards and requirements; second, clarity in every part of the supply chain of the organizational standards and requirements, including the passion for cultural alignment (i.e. consistent commitment to the same health, safety and environment standards); thirdly, a focus by the ODA on enrolling contractors, equipping them to start their own good practices and to drive their own performance; this allows contractors to develop and apply their own processes, fourthly, acknowledgement of the prestige of working on the Olympic site and consequently striking for the best in activities, including health & safety; fifthly, the project scale and the construction phase length, which means initiatives have time to 'bed in', and can be customized to make sure their efficacy is realized; and lastly, belief by workers in the sincere dedication inside organizations, as the message was unchanging and reiterated inside the Olympic site along with time. The determined effort that is put on leadership and engagement of staff, such that the ideal behaviors and attitudes are embedded on site and recognized as the only way of working is identified to be essential to develop the good safety culture across the construction firms. The following points are derived from the London 2012 Olympic project, where they contributed to achieving a positive safety culture.

The first point is organizational commitment. Management needs to realize benefit of leading by example and showing encouraging behaviors, be observable and accessible, and give support where disputing tensions arise. The second point is health and safety oriented behaviors. We can provide tailored seminars and campaigns to make them applicable to workers, and include fascinating activities to engage the workforce. We can also utilize guest speakers to help deliver campaigns and training messages. One can resort to stimulus to encourage good behaviors on site. The third point is health and safety trust. We can resort to different kinds of reward and recognition schemes inside the workplace to encourage good and positive behaviors. We also need to take the management decisions impact into consideration and recognize the human error possibility, and generate opportunities for workers to talk about health, safety and environmental issues and make sure agreed actions are followed up on. The fourth point is usability of procedures. We need to develop risk assessments following a structured process, with participation from skillful workers who are familiar with the work tasks. We also need to make sure workers clearly understand risk assessment and method statements documents, and motivate workers to read risk assessment documents at work. We can also make workers to be involved in conversation around method statements and risk assessments, and we use this as a basis for day-to-day briefings to keep high situational awareness. The fifth point is engagement in health and safety. We need to develop different kinds of reporting methods, interact these with workers, and make every worker confident to talk about health and safety problems with anyone on site. We also need to develop a behavioral-based safety initiative to identify and embed good safety behaviors. The sixth point is peer group attitude. We should allocate time and resources to make workers be able to develop strong and positive working relationships, and ensure workers and managers recognize the significance of creating a safe and encouraging working environment. We should also make the working environment and job a positive experience for workers, encourage them to continue their employment, and reduce absenteeism and turnover where possible.

IV. Management of Change

Management of change (MOC) is a best practice utilized to make sure that safety are under control when a team in a organization makes changes in their facilities, documentation, operations, and personnel. Normally, a business opportunity or need becomes a project and demands changes inside the workplace, and this could pose an influence on people, processes and organizational structure. The need can be as simple as replacing a failed part on a machine or changing the team structure if necessary. MOC is particularly important because, under the situation where changes are made quickly, safety incidents and potentially disasters could possible occur. For example, explosions at the detergent plant reported in the U.S. chemical safety and hazard investigation board's 2001 "Management of Change" report. For related MOC documentation, refer to "Environment, Social, Health and Safety Management System (ESHS MS), MOC Procedure, Document Number: 02/GP/PJ/PR/009/A01" [21]. One prominent benefit MOC provides is that the consequences of unpredicted safety hazards can be avoided via organizing and planning the implementation of change in the facility.

The benefits of MOC can be summarized as follows: first of all, it increases efficiency and productivity of organizing and practicing of changes in a team. Secondly, it reduces harmful effects on system integrity, security, reliability, and stability for business process that is altered. Thirdly, it can provide a stable production environment inside a design team. Fourthly, it guarantees the correct level of technical completeness and testing of systems prior to practicing. Fifthly, it can provide a proper level of management approval and involvement in a team. Lastly, it improves safety for each individual inside a design team during the design process.

V. Emerging Trends in Engineering Design, Teams and Safety

A. Modular Design

Modular design is a type of approach that splits a system to many smaller parts, each part is called a module. Each module is able to be separately generated and then employed in different systems. Each module or component is considered independently regarding health and safety issues.

Modular design in robotics

Modular design can be widely seen in robotics area, as illustrated in Fig. 1. Details are provided in [22].

Figure 1. Modular robotics design.

B. Changeability of Manufacturing

It refers to speedy manufacturing changeability to fulfil customers' needs and react to external impediments and factors. Safety has to be considered in ensuring changes are compatible when manufacturing components are upgraded, modified or substituted. "Changeability" is here employed to be an overarching terminology that encompasses the terms that usually illustrate prevailing paradigms of changing production capacity. Among these terms are "reconfigurability", "flexibility", and "transformability".

C. Emerging Trends in Safety and Health

The status of work related health and safety is affected by many factors: such as changes in demographics, including a changing age profile of the workforce, new technologies that provide new ways to support health and safety and also create new categories of employment, existence of dangerous substances, such as harmful chemicals, exposure to ultraviolet radiation and noise, and concerns over occupational diseases and work-related stress. Emerging trends in health and safety will affect engineering teams and need to be addressed to ensure safety in teams. Some of these are discussed in more detail as follows.

Age

Changes in the workforce's age distribution sometimes have effects for the workers' safety and health. Teams will likely be comprised of members having different ages and experience levels, posing potential concerns regarding health and safety. Correspondingly, efforts are being made to maintain good health and safety among members of the workforce: measures that reduce occupational accident for older workers, measures that reduce occupational diseases rates, and effective rehabilitation programmes. Between 2000 and 2005, the number of workers aged between 15 and 64 in the EU-25 increased by about 8 million. This changing fashion makes it more critical to concentrate on reducing the risk of work related accidents and improving workers' health, especially for the oldest workers.

Chemical risks in small- and medium-sized enterprises

The rate of incidents at work linked with hazardous materials is usually higher in small- and medium-sized enterprises (SMEs) than that of large ones. Approximately 80% of all work related diseases induced by chemical agents are occurred in SMEs, and workers in SMEs exposed to chemical agents usually suffer various health effects. Some of the main preventive measures that companies can implement for dealing with chemical risks are as follows:

- Eliminate hazardous substances and substitute with less hazardous ones
- Application of collective protection acts, e.g., adequate ventilation, engineering controls
- Reduction or minimization of number of workers likely to be exposed
- Reduction or minimization of the intensity and duration of exposure
- Application of appropriate hygiene acts
- Reduction in the chemical agents quantity to the minimum needed for the work
- Use of suitable work procedures, including safe methods for handling, storing and transporting hazardous chemical agents and wastes

Exposure to noise and hearing impairment

Exposing to immoderate noise could cause hearing impairment. Noise-triggered impairment is able to be induced via a one-time exposing to a noise impulse that is over 140 decibels (dB(C)), and exposing to high intensity that is over 85 decibels (dB(A)) sounds a few hours a day for a long time.

Mining, manufacturing, and construction areas have the highest degrees for work related hearing impairment. Noise at work is a universal issue, covering a broad range of industrial sectors. No matter how much equipment and processes are engineered for noise avoidance, occupational workers may still experience hearing loss due to noise exposures external to the work environment. For instance, earbuds and headphones attached to phones and other personal devices like ipods can produce sound levels well in excess of 85 dB (a).

VI. Case Studies

Study I

Situation: In a hypothetical manufacturing plant, a large number of engineering activities such as design, production of parts, assembly, and testing are conducted in a broad range of areas. Some manufacturing processes are performed using automated equipment and others by people, depending on factors such as cost, quality, time, and worker safety and health. The plant makes and assembles heavy machine parts (e.g., fans, pumps, and electronics). The plant usually runs three shifts every day. It has production lines that include conveyers, machining equipment, overhead cranes, and paint-spray booths. The plant heavily relies on natural gas and electricity.

The problems: In the last five months, some plant workers have been having different health issues. The plant's head engineer receives the following information. First, in an assembly area that was installed not long time ago, workers must bend over to the floor all day long to attach some small parts onto a large machine equipment. Some of the workers have already started to show lower back pain, presumably because of the repeated and continuous bending. The issue has turned very serious for one worker to the point that the doctor has informed this worker to stop working for at least three weeks so that his back is able to be recovered. An automatic system was proposed for assembly operation first by the manufacturing engineers that are involved in designing it, however that option was not considered because it is not deemed as economically. So a manual operation was utilized instead, but they did not consider industrial ergonomics as they do not have enough knowledge in that field. Second, a large number of respiratory related diseases are recorded in the past few weeks by workers that are close to paint-spray booths. Most of the materials that are utilized in the booths are recognized as the source of the diseases. The workers supposably do not have any contact with the materials as the booths were made in a way to guarantee that materials get out of the plant via a ventilation system and there is no substances leaking back to the plant. There is not any examination being conducted on the ventilation system or the quality of the air around the booths, thus one is not certain if any materials leak back to the plant from the booths. Third, at the place where metal cutting happens and workers wear protective eyewear, minor eye injuries have been recorded. It is observed that most workers do not usually wear the protective. It is often seen that most eyewear are hanged on hooks. Workers complain the eyewear is not comfortable to put on their head and do not consider as that necessary. The plant manager is aware of this behaviour but disregards such, since forcing workers to wear the eyewear could make the workers unhappy and, therefore, make the plant unproductive. The manger thinks that this may put the plant under a non-competitive situation.

Discussion questions:

Consider the case study in the context of the engineering circle in Section 2.3, and address the questions that follow. Be sure to use the engineering circle to help enhance understand the entire spectrum of issues involved in team design.

a. How would you identify the causes for the health issues?

b. From a requirements and constraints perspectives, what requirements do you think the plant as a team should put forward to achieve safety in the areas mentioned, and what are the current constraints that exist inside the plant?

c. Try to convert the above problem into an explicit mathematical model, i.e., setup the objective function (to represent the health issue), the design variables (to represent the factors that cause the illnesses) and your own constraints.

d. What do you think are some acts that can be implemented to fix the health issues noticed?

e. Do you think that the lead engineer should correct the health issues on his own, or do you think he should get the issues to the manager first? The lead engineer is unsure whether he will get the manager's support in correcting the issues; what can he do if the manager does not provide support?

f. Do you think that some of the health issues happened are because of worker safety and health being inappropriately compromised to make the plant more profitable?

Study II

Considering the hypothetical plant reported in Case Study I again. The lead engineer wants to make sure the plant be able to deliver a healthy and safe working surroundings, so he opts to inquire an engineering safety consulting firm to conduct a safety and health audit for the plant. The consulting firm issues the safety concerns as follows. First, it is noticed that the explosion could possibly happen within the plant in some scenarios due to substantial usage of natural gas in the plant. The consequence of the explosion will cause deaths or serious injuries, and the worst case scenario is that it can damage the building to the point that the building may collapse. The chances of such explosion will go up if there is a large amount of natural gas leaking or the ventilation system of the plant does not work right or certain sensors or controls break down. Furthermore, it is noticed that there is just one natural gas sensor being installed inside the plant, and this sensor is not placed in the central area where natural gas accumulation could happen. Also, the sensor is not connected to either an automatic shut-off system for the gas supply or an alarm. Second, even though maintenance should be conducted every other month on the gas lines, there is no proof showing that the maintenance has ever been conducted. Such maintenance usually entails inspecting and fixing gas leaks. Thirdly, workers have never received any training on recognizing the possibility of explosion or the procedures to implement in order to prevent an explosion. On the contrary, the majority of the workers are not even aware that the possibility of an explosion exist. Further, there is not drafted course of actions relating explosions inside the plant. Fourthly, the plant stores some poisonous substances that are harmful to workers. The way that the material is stored could easily be released and affect a region that is within one kilometer from the plant in the case of a plant explosion. Such incident could harm public members or even worse could pose a death threat on workers.

Discussion questions:

Again, address the questions considering the engineering circle in Section 2.3, to help enhance understanding of the issues involved in team design.

a. What do you think are the unsafe acts and conditions inside the plant?

b. What requirements/constraints does the plant need to propose and implement inside the plant in order to achieve a safe working condition?

c. What uncertainty factors inside the plant do you think that can cause the natural gas leak?

d. Similarly with the case study I, try to convert the above problem into an explicit mathematical model (i.e. setup the objective function (to represent the plant safety issue), the design variables (to represent the potential factors that cause safety problems) and your own constraints.

e. Can the lead engineer opt to pay no attention to or not fully act on the safety concerns given by the consulting firm? If he can, under what conditions and in what instances?

f. If the lead engineer deems that measures have to be implemented to protect safety and health, but the manager disapproves the acts, what is this lead engineer obligated to do?

g. Are any of the issues described above indicating that it is wise to confront safety and health at the beginning of an engineering activity or during the design process rather than later? For example, can you specify some acts that probably cost more to handle the problem as comparing to the cost of addressing the problem during the design process?

VII. Student Assignment

Students are to carry out a group project to design a mobile robot that runs in a maze. The robot needs to locate a water bottle (placed anywhere inside the maze), pick it up, and carry it back to the starting point. In this project, students work as a team. When designing a complex device or system, many engineers (in this case engineering students) from different areas come together in the design process. The students need to cooperate, consider each other's requirements and, where necessary, compromise. Safety is to be considered when designing and constructing the robot since it contains electronics and mechanical parts, which can introduce hazards. The students should refer to the above teaching module when carrying out the project as a team.

Requirements and constraints are as follows:

- The water bottle cannot touch the ground (except after the robot carries it back to the starting point) once it has been picked up.
- The robot cannot cross the boundary of the maze.
- Students cannot touch or intervene with the robot once the robot starts operating.
- When the robot carries the bottle back to the starting point and puts it on the ground, the bottle cannot fall down. It also has to be smoothly and steadily placed on the ground.

VIII. Closing Remarks

Safety is one of the most critical factors one needs to take into consideration in engineering fields and engineering design teams. This paper represents a teaching module of incorporating safety into engineering teams and the design process. The introduction to safety in engineering design and teams, safety documentation, rules and culture in design and teams, management of change, some emerging trends in engineering design, teams and safety, and finally case studies are presented.

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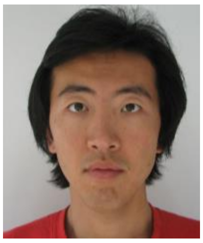

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