NORDIC COURSE DEVELOPMENT COOPERATION IN AN EMERGING FIELD OF ENGINEERING

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ABSTRACT

Four decades ago, a specific engineering BSc study program in Fire Safety Engineering was formed at Lund University, Sweden, and several Nordic universities have since included courses on such subjects in their own BSc og MSc programmes. The field of fire safety engineering encompasses topics from a wide range of engineering disciplines, including mathematics, physics, chemistry and advanced engineering courses such as heat transfer, thermodynamics and fluid dynamics. It is not immediately obvious how to balance the need for knowledge from fundamental, applied and specific courses to be taught within the discipline of fire safety engineering. Long standing cooperation across 12 Nordic universities and research institutions has made this distinction clearer and most recently this network secured Nordic funding for three years for a specific cooperation program in education, including PhD exchange programs and the development of a summer school for students of engineering, focusing on fire safety and energy. Specifically, four of these universities, through the authors of this paper, have been cooperating for a number of years within one of the key courses called „Enclosure Fire Dynamics", the study of how a fire develops in a building and how engineering methods based on classical physics and chemistry can be used to simulate the environment due to fire, allowing engineers and designers to test and compare various possible design solutions regarding building fire safety. This has required careful development of educational material in close cooperation between Nordic universities, following the CDIO principles. The fruitful cooperation has resulted in the production of comprehensive educational material such as textbooks, homework assignments, laboratory instructions and computer labs, to name a few examples of results. Most of the material is free of charge and available on the internet. This paper provides an example of how this has been achieved by a cross-Nordic collaboration on providing and developing educational material in an emerging engineering discipline.

KEYWORDS

Fire Safety Engineering (FSE), Fire Protection Engineering (FPE), Performance-based Codes, Prescriptive Codes, Fire Safety Engineering Education, Fire Safety Engineering Design, CDIO Standards 1, 3, 4, 5, 6, 7.

INTRODUCTION AND RELEVANCE TO CDIO

In this section we shall discuss the emergence of the discipline of fire safety engineering (sometimes termed fire protection engineering) and how the CDIO standards and principles have, in recent years, been helpful in further developing educational programmes in the field. A brief overview of this paper will be presented.

The emergence of fire safety design as a new engineering discipline

Fire safety regulations can have a major impact on many aspects of the overall design of a building, including layout, aesthetics, function, and cost. Rapid developments in modern building technology in the last decades often have resulted in unconventional structures and design solutions. The physical size of buildings increases continually; there is a tendency to build large underground car parks, warehouses, and shopping complexes. The interior design of many buildings - with large light shafts, patios, and covered atriums within buildings connected to horizontal corridors or malls - introduces new risk factors concerning spread of smoke and fire. Past experiences or historical precedents (which form the basis of current prescriptive building codes and regulations) rarely provide the guidance necessary to deal with fire hazards in new or unusual buildings.

At the same time there have been great strides in the understanding of fire processes and their interrelationship with humans and buildings. Advancement has been particularly rapid in the area of analytical fire modeling. Several different types of such models, with varying degrees of sophistication, have been developed and are used by engineers in the building design process internationally.

As a result, there is a worldwide movement to replace prescriptive building codes with ones based on performance. Instead of prescribing exactly which protective measures are required (such as prescribing a number of exits for evacuation purposes), the performance of the overall system is presented against a specified set of design objectives (such as stating that satisfactory escape should be effected in the event of fire). Fire modeling and evacuation modeling can often be used to assess the effectiveness of the protective measures proposed. The need to take advantage of the new emerging technology, both with regard to design and regulatory purposes, is obvious. The increased complexity of the technological solutions, however, requires higher levels of academic training for professionals in fire safety engineering and a higher level of continuing education during their careers. The CDIO principles have been an excellent guide when academians in the Nordic countries have cooperated on developing programmes and individual courses for fire safety engineers.

The CDIO principles and standards

The CDIO Initiative was launched in the year 2000, with the aim of providing students with an education that stresses engineering fundamentals set in the context of Conceiving, Designing, Implementing and Operating engineering activities. The four phases are an abbreviation of the word CDIO (Crawley et al, 2011).

Further, the four phases encompass (Zabalawi, 2018):
Conceive phase: Defining customer needs; considering technology, enterprise strategy, and regulations; developing concepts, techniques and business plans.
Design phase: Creating the design; plans, drawings, and algorithms that describe what will be implemented.
Implement phase: Transforming the design into the product, including manufacturing, coding, testing and validation.
Operate phase: Using the implemented product to deliver the intended value, including maintaining, evolving and retiring the system.

Due to the great advancement in knowledge in the field of fire safety engineering in the last few decades, particularly with respect to fire modeling and evacuation modeling, engineers can now use methods based on fundamental physics and chemistry to simulate the evolvement of a fire in a building and can thus compare various possible design solutions regarding building fire safety. But in order to apply this new knowledge, the building regulatory system must be performance-based, to allow such methods of verification. Older regulatory systems are often based on prescriptive rules, certain rules-of-thumb based on old experience or given values and numbers that often have little to do with fundamental physics and chemistry. It can be difficult to apply new engineering methods based on the advancing knowledge in the field in countries where regulatory systems are dominated by older prescriptive rules.

In this paper we shall therefore discuss Performance-based regulatory systems and how fire safety design based on fundamental engineering knowledge can be applied to complex situations, where the older prescriptive rules can not be applied. We shall briefly describe a Core Curriculum for fire safety engineering and, as an example, one specific fundamental course within the curriculum, called Enclosure Fire Dynamics. We shall then give examples of educational programmes in fire safety engineering offered at a number of Nordic universities and discuss how the close cooperation between Nordic academemians in the field has allowed a sound development of the fire safety courses and programs, in line with the CDIO principles and standards.

PERFORMANCE-BASED BUILDING CODES

Variations of performance-based regulation regimes have been adopted in many developed countries around the world for regulating such aspects as building and fire safety, air and water quality, consumer product safety, energy efficiency, food safety and many other fields. With regard to building and fire safety, there has been a worldwide tendency in recent decades to facilitate a transition from prescribed to performance-based building regulations.

It has been argued that the main purpose of building regulations is to serve as a legal tool to provide minimum social needs with regard to the built environment, without causing excessive costs to society. This objective can be achieved by regulations composed of a mixture of prescriptive and performance requirements. To clarify the terms further, a prescriptive rule would typically be of the type: “Escape routes shall not exceed 30 meters in length”, while the corresponding performance-based rule could typically be of the type “An escape route shall be designed in such a way that the occupants may exit the building safely in case of fire”. The prescribed rule presents an exact measure and can be easily verified, but is inflexible, while the performance-based rule states a goal, allows flexibility and various different design solutions, but verifying the fulfillment of the goal can be a challenge.

In many parts of the world an effort has been made to move from prescriptive demands in building regulations toward an increased use of performance-based demands. In many countries the shift has been gradual and careful, while other countries have opted to make comprehensive changes to their building codes in a single step, as described by Meacham (2010). The Society of Fire Protection Engineers (SFPE, 2015) has published guidelines on performance based codes and international entities such as the the International Standards Organization (ISO) and the International Code Council (ICC) have produced guidelines, standards and codes on this subject.

In the 1970s regulatory agencies of all types began to reconsider the traditional prescriptive approach to regulations, seeking ways to clarify the intent of regulation, reduce regulatory burden, and encourage innovation without compromising the level(s) of performance delivered. This gave rise to consideration of functional, objective-based or performance-based approaches to regulation. In the building regulatory environment, the hierarchy outlined by the Nordic Committee on Building Regulation (NKB, 1978) became a widely adopted model. Figure 1 shows an outline of the NKB hierarchy of demands.

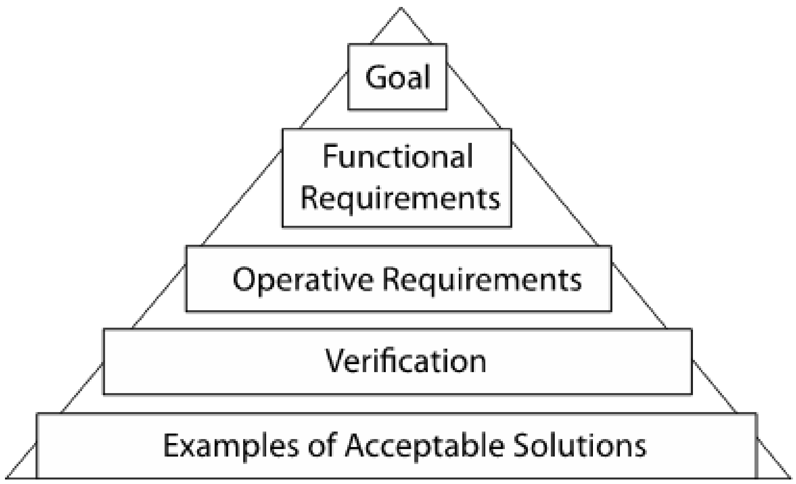

Figure1. The NKB hierarchy of demands.

In the NKB model the regulatory provisions are based on a set of broad societal goals, at the top of the pyramid. Through increasing levels of detail, functional requirements and operational requirements for buildings are described. Instead of prescribing a single set of design specifications for compliance, the approach outlines the need for instructions or guidelines for verification of compliance, in the next level. This could include engineering analyses, test methods, etc, and would be used to demonstrate compliance with the operative requirements. Finally, at the bottom of the pyramid one finds “Examples of Acceptable Solutions”. These are supplements to the regulations with examples of solutions deemed to satisfy the requirements, which may be prescriptive. The NKB model is attractive because it places the focus on societal (policy-level) goals and allows for a variety of forms of regulatory provisions to provide the detail required to demonstrate compliance.

Any regulatory regime must find a balance between how tight controls should be in promoting consistency and accountability versus how much discretion should be granted in promoting flexibility and innovation. The prescriptive approach emphasizes control and accountability. The performance-based approach desires to promote flexibility with accountability for results.

Some of the potential benefits of moving toward a performance-based regulatory regime are that this may lead to greater effectiveness in reaching specific regulatory objectives, greater flexibility in means of adhering to the regulation and increased incentive for innovation, resulting in buildings that are to a greater extent designed for the intended use.

However, the performance-based approach demands professional designers with a deep knowledge of the technical fundamentals, such as mathematics, physics, chemistry, thermodynamics to name only a few engineering disciplines. When developing the context, learning outcomes and curriculum of any fire safety engineering programme or courses, the CDIO standards form an excellent bases to build on.

In the next section we shall give a brief description of the fire safety engineering design process and how performance-based demands are typically presented in building codes. Such design methods must often include verification that certain design limits are met, which frequently requires the use of fire safety engineering calculations or modeling.

Further, we shall give an example of how a core curriculum for fire safety engineering education has been developed and give an example of how one of the fundamental courses in that curriculum was set up, providing simple engineering relations for solving engineering problems in performance-based fire engineering design.

THE FIRE SAFETY ENGINEERING DESIGN PROCESS AND CODE DEMANDS

Various sets of rules, procedures and guidelines on how to use fire safety engineering methods in building design have been developed over the last few decades. For example, it is known that humans can tolerate a limited amount of heat and a limited amount of toxic gases for a short time and some minimum visibility must be guaranteed if building occupants are to evacuate a smoke filled environment effectively.

A general consensus on a number of such limiting values has been established and published in standards, guidelines and a large number of national building regulations. The limiting values can vary somewhat between countries, but the performance based demands are essentially similar. For example, when the design goal regards the safety of building occupants, a demand is made that smoke does not hinder safe evacuation. This entails that the smoke level never reaches further than roughly 2 m above floor level, or that the concentration of carbon monoxide in the smoke is below 2000 ppm. A good description of the fire safety engineering design process and limiting design values is for example given in the Nordic Standard *INSTA 950 – Fire Safety Engineering – Comparative method to verify the safety design in buildings* (INSTA, 2014). The INSTA 950 Standard is valid in all the Nordic countries: Norway, Sweden, Denmark, Finland and Iceland. Several other standards and guidelines are available to the reader, such as the *SFPE Guide to Performance-Based Fire Safety Design (2015).*

The prescribed and the performance-based approach to design

When preparing a trial fire safety engineering design for a building an engineer will often base the initial design on pre-scribed demands in the building code, or pre-accepted solutions, as discussed in the previous section and presented as the lowest pier in the triangle depicted in Figure 1. For simplicity and expediency, it is thus quite common that buildings are initially designed against the threat of fire using only prescriptive demands or pre-accepted solutions, However, a deviation from one or more of these solutions may be in the interest of the buildier. For example, the fire safety design of a simple two-storey school building may easily be based on prescriptive demands or pre-accepted solutions, but when the owner decides that the stairway between the floors must be open, allowing smoke to travel between the floors, the designer may greatly benefit from utilizing calculations and fire models to design heat and smoke extraction of some kind, thus fulfilling the performance-based demand of a smoke free escape environment.

Figure 2 shows some examples of how design solutions can be verified when using prescriptive and performance-based fire safety engineering design methods, or a combination of both. Thus, compliance with fire safety regulations can be demonstrated by constructing the building in accordance with prescribed or pre-accepted solutions as defined by national building authorities. Alternatively, given that the national building authority in question allows and has set performance-based demands, a design solution can be based on fire safety engineering methods as a means of proving that the fire safety is satisfactory. This, however, demands that the designer has a fundamental understanding of the subject “enclosure fire dynamics”, the study of how the outbreak of a fire in a compartment causes changes in the environment of the enclosure.

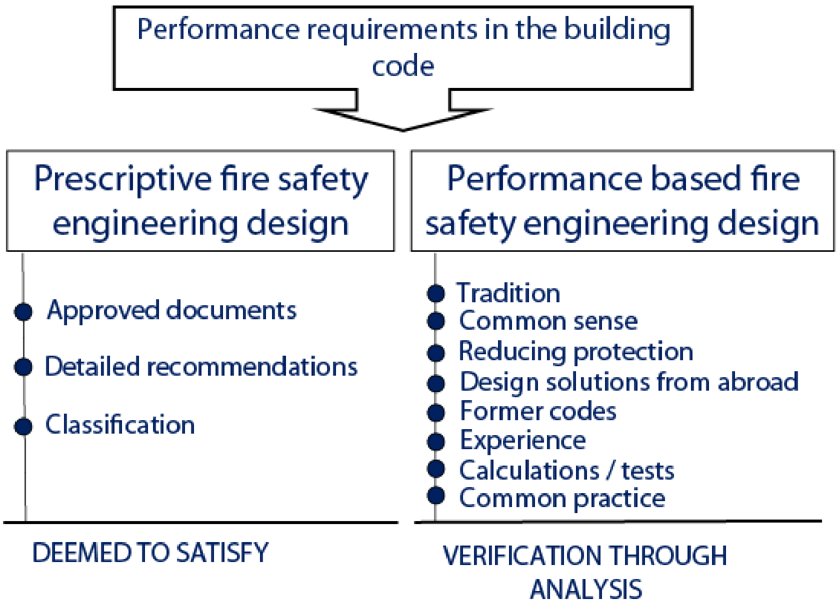

Figure 2. Examples of ways to verify compliance to demands presented in building codes using either prescriptive or performance-based fire safety engineering methods, or a combination of both.

In fire safety engineering design the engineer can use various tools to verify that the proposed design fulfills certain fire safety objectives, or design goals, and results in safety levels that are acceptable to society. The design goals can for example be safe evacuation of people, preventing building collapse, protecting valuables, ensuring safety of rescue teams in case of fire, to name some of the most common design objectives. In the process of verifying that design goals are met, the designer can use rational argumentation, traditional solutions, laboratory tests, common sense, and many other tools. When using calculations and models, these predominantly have a basis in classical physics, chemistry and thermodynamics, derived from scientific principles, empirical calculations and laboratory test results. The modeling techniques and calculational methods used for this purpose are the main focus when studying enclosure fire dynamics.

CORE CURRICULUM IN FIRE SAFETY ENGINEERING

The field of fire safety engineering encompasses topics from a wide range of engineering disciplines as well as material of unique interest to fire safety engineering. It is not immediately obvious which of these topics of interest should be addressed in courses for fire safety engineering students.

When developing courses for fire safety engineering students the authors were greatly assisted by the publication *A Proposal for a Model Curriculum in Fire Safety Engineering*, by Magnusson et al. (1995), which identifies the contents of the background, fundamental, and applied courses that may be taught within the discipline of fire safety engineering. The Society of Fire Protection Engineers (SFPE 2010 and 2013) has expanded on the curriculum in recent years for both bachelor's and master's programs, but the description below is based on the work of Magnusson et al. The fundamental courses listed by Magnusson et al are divided into five modules:

- Fire fundamentals
- Enclosure fire dynamics
- Active fire protection
- Passive fire protection
- Interaction between fire and people

These modules are interlinked to a considerable extent, and it is often a question of preference where to include borderline topics and where to present a summarized background. Also, it is not obvious where to strike the balance between material presented in the fundamental modules and material assumed to be prerequisite knowledge from basic courses in physics, chemistry, fluid mechanics, etc. We assume that the student has a basic knowledge of mathematics, physics, and chemistry.

The course Enclosure Fire Dynamics

As an example, one of the fundamental courses listed above will be further discussed here; Enclosure Fire Dynamics, the study of how the outbreak of fire in a compartment, causes changes in the environment of the enclosure. In many of the Nordic universities where fire safety engineering is taught, the textbook Enclosure Fire Dynamics by Karlsson and Quintiere (1999) is used as main literature. The textbook does not attempt to provide an in-depth study of all the phenomena involved, but rather to present the most dominating mechanisms controlling an enclosure fire and to derive some simple analytical relationships that can be used in practice. In view of the increased use of calculational procedures and computer models in building fire safety engineering design, the main purpose of this textbook is to:

- provide an introductory, basic understanding of the phenomena of interest and present some examples where these can be used in practice;
- derive the equations from first principles in order to give the student a true sense of the validity of the procedures in each design situation; and
- compare the derived equations with experimental data to provide a sense of confidence in the analytical results.

Additionally, laboratory experiments, computer labs, design exercises are discussed and described in the textbook.

EXAMPLES OF PROGRAMMES AND COURSES IN FIRE SAFETY ENGINEERING

At several Nordic universities, fire safety engineering courses are presented in a great variety of ways. Some universities teach one or two fire related courses as a part of a BSc or MSc engineering degree, other universities provide full BSc fire safety engineering programmes and some provide a full MSc fire safety engineering degree on top of any BSc degree in engineering.

To mention a few examples, Lund University, Sweden, offers an extended BSc degree in Fire Protection Engineering, a 3,5 year programme with around 50 students per year and Lulea Technical University, Sweden, offers a similar BSc programme. Lund University also offers an International Erasmus Mundus Master in Fire Safety Engineering (IMFSE), which they run together with Ghent University and The University of Edinburgh. This is a 2 year program with around 20 students/year, where the students spend 1/3 of the time at each of the three universities.

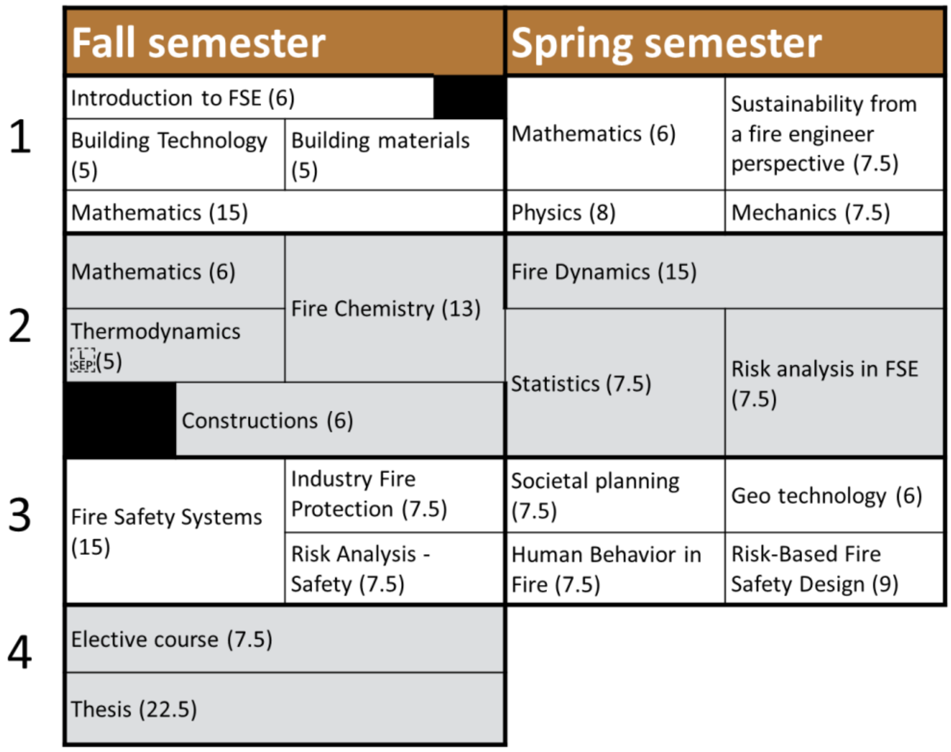

Figure 3. A schematic of the 3,5 year extended BSc programme in Fire Protection Engineering offered at Lund University, Sweden.

As an example of these and other programs, Figure 3 shows a schematic of the 3,5 year extended BSc Fire Protection Engineering programme offered at Lund University where the numbers on the left hand side represent the years of study.

Graduates from these educational programmes have been very much appreciated by employers, such as industry, government and local authorities and there has been no unemployment registered for Fire Safety Engineers (or Fire Protection Engineers) in Sweden in the last decades. The graduates from these programmes have on average higher salaries than graduates from other engineering programmes, such as Civil Engineering and Mechanical Engineering. Applications to enter the programmes have been far greater in numbers than the intake over many years. In view of these facts it can be clearly stated that the Fire Safety Engineering (or Fire Protection Engineering) programmes in Sweden have been very successful in general.

When examining the course descriptions for these programmes, it is clear that the courses, and the educational programmes in general, fulfill to a high degree the relevant CDIO Standards. This is especially so for Standard 2 – Learning Outcomes, Standard 3 – Integrated Curriculum, Standard 4 – Introduction to Engineering (see top of Figure 3), Standard 5 -Design-Implement Experiences, Standard 6 – Engineering Workspaces and Standard 7 – Integrated Learning Experiences.

COLLABORATION OF NORDIC ACADEMICS IN FIRE SAFETY ENGINEERING

In addition to the programmes offered at Lund University and Lulea Technical University described above, various additional degree programs and/or single courses on fire safety engineering are provided at several other Nordic universities, such as Denmark Technical University (DTU), Aalto University, Finland, Norwegian University of Science and Technology (NTNU), Norway, Western Norway University, Haugesund, Norway, and University of Iceland, to name only a few. The academics at these educational establishments, involved in fire safety engineering education, have been collaborating for the last many years on course development and production of educational material, as well as organizing conferences and collaborating in research.

This informal cooperation through the years was formalized in the year 2015, when a core group of Nordic fire safety engineering educators and researchers started the organisation Nordic Fire and Safety Days (NFSD). The main activity was to hold annual conferences on fire safety engineering issues in the Nordics and enhance Nordic collaboration in the field. Since then this platform has grown and the conference has become a meeting point for educators, researchers, students and professionals interested in fire protection and safety issues in general.

A further step was taken in the year 2020, when this network of educators and researchers in the field applied for and received funding from Nordic Energy (a funding organization linked to the Nordic Council of Ministers) to focus on fire safety and risk management of buildings and energy infrastructure. The network has now organized summer schools, webinars and educational opportunities for professionals, in line with the CDIO emphasis on continuing education.

Additionally, the authors of this paper have been collaborating on educational material for some of the fundamental courses in the fire safety engineering programmes, specifically the course Enclosure Fire Dynamics. Three of the authors have received four grants from Erasmus+ Staff mobility for teaching. Two of the authors have now prepared a second edition of the textbook by Karlsson and Quintiere (1999) and other authors have contributed towards teaching material, such as Power Point slides, homework assignments, description of laboratory experiments, reading instructions for students, detailed suggestions for certain problem solutions and descriptions of computer labs for simulating fires and evacuation. All this educational material, which the authors and others have collaborated on developing, is available for free at the website of the International Association for Fire Safety Science, www.iafss.org.

CONCLUDING REMARKS

The CDIO Call for Paper September 2021 states that „The CDIO collaborators recognize that engineering education is acquired through programs of varying lengths and stages in a variety of institutions and that educators in all parts of this spectrum can learn from practice elsewhere". This paper provides an example of how this has been achieved by a cross-Nordic collaboration on providing and developing educational material in an emerging engineering discipline, Fire Safety Engineering.

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