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Nov svetovni podnebni dogovor

Konec meseca novembra 2011 naj bi se pričel podnebni vrh v južnoafriškem Durbanu. Predvidoma se bo nov sveženj okoljsko-podnebnih pobud sprejel leta 2015. Po pričakovanjih, se za Evropsko unijo (EU) ne bo kaj dosti spremenilo, pričakuje pa se zaostreno trgovanje z emisijami. Politike znotraj EU Durban ne bo spremenil, saj še naprej velja 20% znižanje emisij v EU do leta 2020. Pričakuje pa se strožja energetsko-okoljska politika do leta 2050, ko (naj bi bile) emisije znižane za 80%. Ocenjuje se, da bi bilo za dosego teh ciljev potrebno vložiti 270 milijard evrov na leto oz. 1,5 odstotka BDP. Za energijsko učinkovitost stavb naj bi se namenilo 75 milijard, za energetska omrežja 30 milijard, za čistejši in bolj učinkovit promet pa 150 milijard. Pri prometnih ukrepih se pričakuje 175 do 300 milijard letnega prihranka na področju goriv. Zaradi čistejšega zraka, pa naj bi se znižali tudi stroški zdravstva.

Razveseljiva novica je, da naj bi tudi Kitajska uvedla pilotno trgovanje z emisijami oz. emisijskimi kuponi v šestih ali osmih industrijskih območjih. Pričakuje se tudi poenoteno trgovanje z emisijami, ki naj ne bi bilo več vezano na države članice oz. podpisnice sporazumov.

Zanimivo je, da Evropska podnebna fundacija napoveduje delež električne energije do leta 2020 po virih tako, da naj bi se delež jedrskih elektrarn do leta 2030znižal z 29% na 17%, poraba fosilnih goriv naj bi se znižala z deleža 47% leta 2020 na 33% do leta 2030, delež obnovljivih virov energije pa naj bi se z deleža 24% do leta 2020 povečal na kar 50% delež do leta 2050. Menim, da je ta ocena zelo optimistična, še posebej dejstvo, da naj bi se jedrski delež znižal. Po moji oceni, bo prav nasprotno, delež jedrske energije bo do leta 2030, oz. do 2050 naraščal, šele nato lahko pričakujemo povečanje deleža obnovljivih virov pri proizvodnji električne energije.

Slovenija ima srednjeročni načrt znižanja emisij, vendar bo izpolnitev zavez zelo zahtevna. Finančna in gospodarska kriza pa ne more in ne sme biti izgovor, lahko jo le izkoristimo kot nov zagon prizadevanj na področju znižanja toplogrednih izpustov.

A new global climate commitment

At the end of November 2011, a climate change summit in Durban, South Africa, is expected to begin. A new set of environmental and climate change initiatives are expected to be adopted in 2015. It is foreseen that the policy in the European Union (EU) will not change much, while there will be a tightening of emissions trading. The Durban policy within the EU will not change; the EU is still subject to 20% reduction in EU emissions by 2020. However, more stringent energy and environmental policy is expected by 2050, when emissions are expected to be reduced by 80%. To achieve these objectives, investing €270 billion per year, or 1.5 percent of GDP is estimated to be needed: €75 billion for improving energy efficiency of buildings, €30 billion for energy networks, and €150 billion for a cleaner and more efficient transportation. Annual savings from €175 to 300 billion are expected in fuel consumption with traffic measures. Health costs are expected to be reduced due to cleaner air.

The most encouraging news comes from China, which should also introduce pilot emissions trading scheme or allowances in six or eight industrial areas. In the EU, uniform emission trading is expected, which would no longer be tied to Member States.

Interestingly, the European Climate Foundation announced the share of electricity by source by the year 2020, predicting that the share of nuclear power plants will decrease from 29% to 17% by 2030; consumption of fossil fuels will be reduced from 47% in 2020 to 33% by 2030; the share of renewable energy sources will increase from 24% in 2020 to 50% by 2050. I believe that this estimate is extremely optimistic, especially the fact that the nuclear share will decrease. In my estimation, the share of nuclear energy by 2030, will even increase to 2050, and then we can expect an increase in the share of renewables in electricity production.

Slovenia has a medium-term plan for reducing emissions, but will very difficult meet the commitments made. The financial and economic crisis cannot and should not be an excuse; it can only be used as a new impetus to efforts in reducing greenhouse emissions.

Krško, October, 2011

Andrej PREDIN

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PROVIDING MAINTENANCE SERVICES TO NUCLEAR POWER PLANTS: THE ROLE OF SAFETY CULTURE

POMEN VARNOSTNE KULTURE PRI IZVAJANJU VZDRŽEVALNIH STORITEV V JEDRSKIH ELEKTRARNAH

Andrej Androjna[ℜ], Zoran Račič

Keywords: Safety culture, nuclear power plant, maintenance

Abstract

After explaining basic terms and the relationships between the organizational and safety cultures, this paper illustrates the characteristics of the safety culture in the nuclear industry and, more specifically, in the maintenance of nuclear power plants (NPP). It further discusses the role of safety culture in organizations of external maintenance providers. The results clearly show that the standards and criteria of the safety culture applicable to plant employees are equally valid for external service providers. For the latter, assuring the highest levels of safety culture is a challenge, especially for those who do not provide services solely to the nuclear industry. The case on a leading Slovenian nuclear services provider, NUMIP d.o.o., illustrates its methods and activities for the continual improvement of safety culture in the organization.

Povzetek

Po razlagi osnovnih terminov in relacij med organizacijsko in varnostno kulturo, članek opiše lastnosti varnostne kulture v jedrski industriji, pri čemer je posebna pozornost posvečena vzdrževanju. Nadalje je opisan pomen varnostne kulture v organizacijah zunanjih izvajalcev vzdrževanja. Zaključki jasno kažejo, da so standardi in kriteriji, ki veljajo za zaposlene v jedrskih elektrarnah, veljavni tudi za zunanje izvajalce. Za zadnje, še posebej za tiste, ki ne izvajajo storitev le v jedrski industriji, je to velik izziv. Metode in aktivnosti za nenehno izboljševanje

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varnostne kulture v organizaciji so opisane na primeru vodilnega slovenskega storitvenega podjetja v jedrski industriji, NUMIP d.o.o.

1 INTRODUCTION

The generation of energy is closely associated with responsibility: even more so, when it comes to nuclear energy. In this specific branch, the responsibility can be directly translated into the safety culture. In 1979, there was an accident at the Three Mile Island (TMI) NPP in Pennsylvania, USA, and a quarter of a century has passed since the Chernobyl accident. As a consequence of TMI, more intensive analyses of the impact of the human factor on the safe operation of NPPs began. It was after the Chernobyl accident, when the term "safety culture" was actually coined. Currently, the whole world is observing another disaster at Fukushima Daiichi in Japan. As opposed to the two previously mentioned accidents, the latter has been caused by natural phenomena that exceeded the design bases. Future analyses will show, whether or not a human factor might have played any different role in either the emergency response or in the mitigation of consequences. However, it is the extent of the consequences of the Fukushima disaster that will dictate strong additional requirements to the entire nuclear industry, and very likely also postpone the nuclear renaissance.

Whatever the end result may be, it is of crucial importance to operate the existing and future fleet of NPPs safely. Closely linked to the plant operation is its maintenance. Due to extensive peaks during outages in terms of required maintenance personnel and their special knowledge and skills, it is a common practice throughout the world to engage qualified external providers of maintenance services. Understanding that nuclear energy is different, these providers need to develop and maintain, in addition to the required technical knowledge and skills, an organizational culture that clearly involves a high level of safety culture.

Safety culture is an imperative and requires full attention in all activities related to nuclear power generation. It is one of the main differentiators of nuclear vs. conventional service providers, and also one of the criteria against which customers evaluate service providers. In the not-so-distant past, they were evaluated solely by auditing their quality management system, whereas today several other criteria are applied apart from the two aforementioned: occupational safety, operational excellence, continual improvement, technical competence, financial stability etc. For that reason, maintenance service providers to NPPs must continually develop their competences and culture if they want to stay and grow in the nuclear industry. In this way, hand-in-hand with plant operators, they promote responsibility in the process of safe, clean and competitive power generation.

2 ORGANIZATIONAL AND SAFETY CULTURE

The terms "organizational culture" and "safety culture" are frequently discussed in different contexts. Managerial and sociological sciences still do not uniformly interpret the term "organizational culture", Androjna, [1]; henceforth, both terms will be discussed from the perspective of nuclear power generation, which considers safety culture to a key ingredient of successful operation of each NPP.

The following definitions of organizational and safety cultures have been most commonly used in recent years, INPO, [14]

> "**Organizational culture** is the shared basic assumptions that are developed in an organization as it learns and copes with problems. The basic assumptions that have worked well enough to be considered valid are taught to new members of the organization as the correct way to perceive, think, act, and feel. Culture is the sum total of a group's learning. Culture is for the group what character and personality are for the individual."

In addition to a healthy organizational culture, each NPP, because of the special characteristics and unique hazards of the technology (radioactive by-products, concentration of energy in the reactor core, and decay heat) needs a strong safety culture.

> "**Safety culture:** An organization's values and behaviours - modelled by its leaders and internalized by its members - that serve to make nuclear safety the overriding priority."

Schein [17] describes the culture as a pattern of basic assumptions – invented within a certain group when it learns to manage the challenges of external adjustments (how to survive) and internal integration (how to stay together) – which have developed over time and are transferred from one generation to another. His simplified definition says: "the culture means how we do business here". It is important to note that culture is not just an inherent characteristic of a group but rather a consequence of a historic group experience.

Earlier sources describe safety culture in different ways; INSAG [7] made the first formal definition of the concept:

> "Safety culture is that assembly of characteristics and attitudes in organizations and individuals which establishes that as an overriding priority nuclear plant safety issues receive the attention warranted by their significance."

INSAG-4 did not describe why the term "safety culture" was chosen. Even though it is often understood to be a component of the organizational culture of a NPP, Apostolakis and Wu [3] do not agree with such a distinction:

> "When the subject is culture, we must question the wisdom of separating safety culture from the culture that exists with respect to normal operation and power production. The dependencies between them are much stronger because they are due to common work processes and organizational factors."

The three-level model of safety culture illustrated in Table 1 [10] is a concept developed from Schein's three levels of culture model. That the examples in the model are for illustrative purposes only must be taken into account, as they do not reflect a situation in a specific organization. For the same reason, there are no logical relations among the examples of artefacts, espoused values and basic assumptions.

Table 1: *Three-level model of safety culture*

Level	Example
Artefacts - objects - language - stories - rituals - behavior	Safety policy statement Zero lost time accidents The day the boss broke his ankle Safety award presentations Use of safety equipment
Espoused values	Safety is the top priority Zero tolerance for safety deficiencies Blame-free work environment Errors are learning opportunities
Basic assumptions	Accidents are caused by carelessness Some people are accident-prone Risks have to be taken to achieve targets Safety can always be improved Accidents are avoidable A properly designed plant is inherently safe

It should be appreciated that artefacts are the easiest to observe, but simultaneously the most difficult to interpret the meaning of [10]. Knowledge of espoused values will help with the meaning, but it is only when the basic assumptions are understood, that the meaning of the components at the artefact level will become apparent.

Safety culture should link good practices and codes of conduct, as well as create an open environment for different information sources, which promotes learning [6].

3 ATTRIBUTES OF SAFETY CULTURE

Many sources address the attributes of safety culture in nuclear power generation in different ways. Therefore, it is interesting to examine Alexander's work, which systematically analyses the eleven most cited sources discussing the attributes of safety culture [2]. Among them were the most respected global institutions in the field of nuclear power generation [7-17]. Alexander analysed a total of 24 attributes and selected those that are most commonly agreed as representing the basis of safety culture. In some cases, the attributes were only different by name but essentially the same by content, hence six specific attributes were selected:

- Management commitment to safety,
- Communication,
- Learning culture,
- Problem identification,

- Roles and responsibilities,
- Technical knowledge.

Apart from the identification of key safety culture attributes, Alexander also defined their relationship – see Figure 1 [2].

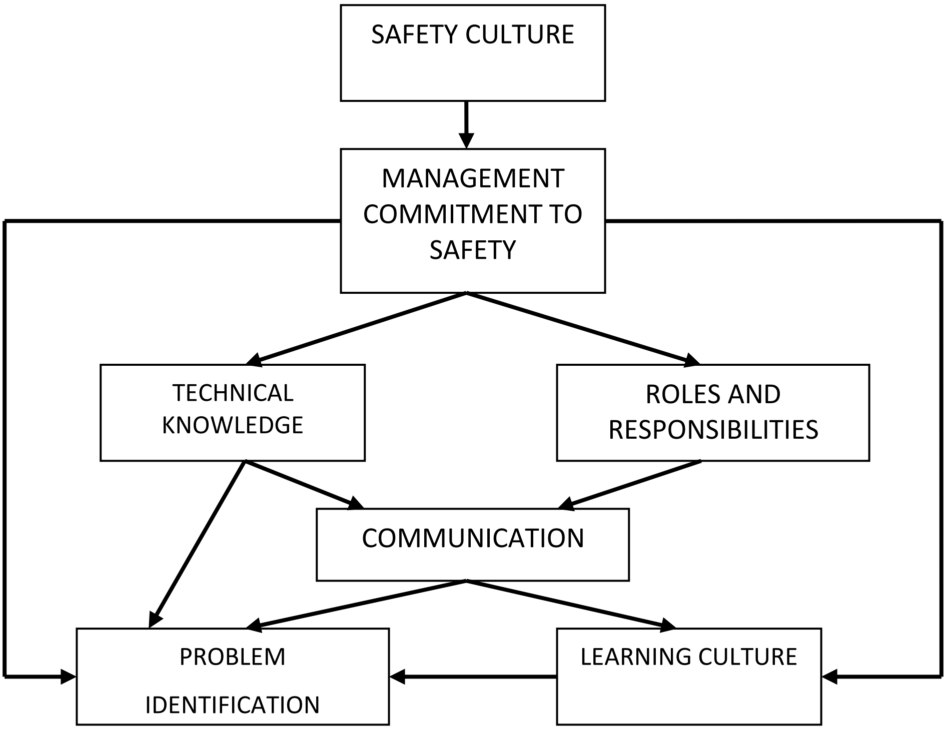

Figure 1: *Relationship of safety culture attributes*

The arrows in the figure can be interpreted as "...is a good indicator of...", hence the attributes are actually not independent.

It is interesting to compare the context of the attributes selected by Alexander [2] with the list of safety culture components used by the US NRC [16], which are in line with the INPO terminology:

- Work control,
- Decision-Making,
- Work Practices,
- Resources,
- Operating experience,
- Self- and Independent Assessments,
- Corrective Action Program,
- Willingness to raise concerns,
- Preventing and detecting retaliation,

- Safety policies,
- Accountability,
- Organizational change management,
- Continuous learning environment.

The comparison confirms that most of listed components correspond to the safety culture attributes defined by Alexander [2].

4 SAFETY CULTURE IN MAINTENANCE OF NPPs

For the discussion of the role of the safety culture for the external maintenance services providers, it is suitable to explore the characteristics of safety culture in NPP maintenance, Androjna, [1]. They need to be distinguished not only from the NPP operation but also from the conventional maintenance, IAEA, [9].

Apart from operations, the maintenance of NPPs deserves special attention due to the potential direct or indirect impact of its activities on equipment reliability. The effects of inappropriate maintenance can cause plant shutdowns and impact plant safety.

The role of maintenance in the NPP is to maintain the built-in safety, reliability and availability of plant structures, systems and components. As NPPs are becoming part of increasingly competitive markets, the requirements for maintenance cost reduction are increasing, which can consequently impact safety culture in maintenance.

The IAEA lists the following reasons that imply that the maintenance of NPPs is unique and requires special attention [9]:

- Maintenance has an indirect effect on operational safety, based on the level of skill of the plant staff and on the:
    - Knowledge of the personnel involved in operational activities;
    - Use of calibrated and approved tools and instruments;
    - Technology approved for maintenance and operating procedures/instructions;
- The complexity of the work performed, involving different disciplines (for plant staff and contractors alike).
- Special work constraints such as:
    - Special isolation of components;
    - Components that are not accessible during plant operation;
    - Work in a radiological environment in accordance with the as-low-as-reasonably achievable (ALARA) principle;
    - Involvement of regulatory or independent bodies during in-service inspection, surveillance tests, etc.
- The delayed effects of maintenance work, resulting from low quality work not being seen until the start-up process, which can cause an interruption or delay in starting up.

- Cost reductions for improving competitiveness in a plant fleet that grows older and needs more maintenance.

In the context of NPP maintenance, "safety culture" means the overall management and control of maintenance process in all modes of plant operation. Safety culture is reflected in the conduct of activities and in the qualifications of personnel. If the latter are high, maintenance personnel excel in the preparation and execution of tasks in accordance with safety, quality and technical requirements. Personnel need to be qualified, organizations certified and maintenance procedures approved.

To maintain a strong safety culture in the context of maintenance management, the procedures should define proper work flow and address the following, IAEA, [5]:

- Job planning, including writing proper instructions and/or procedures for each maintenance activity;
- Proactive planning, incorporating analysis of risks for disturbances and continuous awareness of what could go wrong;
- Specification for close-out purposes;
- Mechanisms to deal with contractors;
- Interdepartmental, intercraft and work team coordination;
- Operational prioritization;
- Planning of shutdown and start up and associated coordination;
- Maintaining an updated schedule of work activities for unplanned shutdowns;
- Pre-job briefings;
- Ensuring accurate control and documentation before performing the task, during the task and upon completion of work activities;
- Openness to early warning signals, delays, disturbances, etc.;
- Clear accountability at all stages of the process;
- Procedures for handling work activities which cannot be finalized as planned;
- Providing for post-maintenance testing.

5 ASPECTS OF SAFETY CULTURE FOR EXTERNAL MAINTENANCE SERVICES PROVIDERS TO NPPs

NPPs use external maintenance services providers to a great extent, especially during outages. Due to the fact that various external maintenance services providers are involved, the following factors need to be achieved for maintaining safety culture of the plant, IAEA, [9]:

- Contractors are qualified to do the job, and the plant ensures that their qualifications are updated;
- Contractor staff members receive good training, not only in basic nuclear knowledge but also in plant specifics, quality assurance (QA) and radiological protection, and in the safety aspects related to their specific jobs;
- Supervision from in-house personnel may vary in detail, depending on the activities and the type of contractors involved in the job, but should always be in accordance with safety standards;

- The maintenance organization should keep a set of systematic criteria to generate milestones;
- Contractors follow and comply with plant regulations that impact their jobs;
- Contractors ensure that they have proper internal coordination;
- Contractors are evaluated by the nuclear power plant (e.g. quality, safety, human performance issues);
- Contractors are encouraged to share their experience after an outage in an open and frank manner;
- Long-term relationships with contractors may be a good solution to support a strong safety culture. This includes the definition of common objectives for contractors and plant staff.

It is a paramount objective that the external personnel have a good understanding of the safety standards of the plant they will be working at. Those standards are the same for both plant employees and contracted workers. To meet the safety standards, a long-term partnership between the plant and the service providers is strongly recommended, IAEA, [9].

For the external maintenance services providers, safety culture also is very important from a business perspective, as it is one of the key evaluation criteria for their qualification, i.e. listing them on the Qualified Supplier Lists per nuclear customers' Quality Assurance programs, EPRI, [5].

6 ASSURING HIGH LEVEL OF SAFETY CULTURE FOR EXTERNAL MAINTENANCE SERVICES PROVIDERS

It is important to understand that NPP operators, external providers and all their employees share the responsibility for protection of public health and safety, NEI, [15], even though the ultimate responsibility for nuclear safety always remains with the plant personnel, INPO, [12]. Hence, it is an imperative to carry out activities safely, in accordance with codes and technical standards and simultaneously meeting the highest ethical standards.

All individuals need to be safety conscious, hence appreciate safety as a number one priority. Every individual should appreciate the continuous need for identification of potential safety hazards and their removal.

Even with the state-of-the-art technology in the nuclear industry, incidents related to insufficient safety culture keep occurring. Consequently, it is necessary to be aware of early warning signs, which enables timely corrective actions. Table 2 shows five stages of organizational decline, which illustrate the progressive consequences if the decline is not recognized and acted upon early enough.

***Table 2:** Five stages of organizational decline model, IAEA, [10]*

Stage	Name of Stage	Characteristic of stage
1.	Over-confidence	Good past performance leading to self-satisfaction.
2.	Complacency	Occurrence of minor events that are subjected to minimum self-assessment, and delay in improvement programmes.
3.	Denial	Number of minor events increases, with possibly a more significant event. These are treated as isolated events. Findings from audits are considered invalid. Analysis of root cause not done.
4.	Danger	Several potentially serious events occur, but management and employees reject criticism from auditors or regulators, by considering their views biased. The oversight function is afraid to confront management.
5.	Collapse	Regulator intervenes to implement special evaluations. Management is overwhelmed and may need to be replaced. Major and very costly improvement needs to be implemented.

This kind of decline can be avoided with critical self-assessments in the organization and the consequent implementation of action plans with clear priorities for root causes elimination.

The combination of learning culture, problem identification and communication (see Section 3) is also extremely important. It enables the organization as a whole to learn from individual mistakes, and sharing the lessons learned between the employees. A necessary prerequisite is that the individuals are not afraid of the consequences of their mistakes; otherwise, there is a very high probability that they would not admit them, which can lead to the deterioration of nuclear safety, IAEA, [10].

In the analysis of importance of organizational factors that affect safety culture, IAEA, [11], continuous improvement was ranked the highest. This is equally relevant for the external service suppliers; therefore, a solid quality management system is crucial to support continuous improvements. A well-established and controlled quality management system is therefore one of the key preconditions for an external services provider to participate in the maintenance of NPPs.

In that respect, it is interesting to mention a case that occurred during the construction of a new NPP, Olkiluoto 3, in Finland. The main contractor, together with its subcontractors was not meeting the required safety standards due to, STUK, [18]:

- Insufficient experience of subcontractors, for whose selection price was a key criterion, and
- Ineffective quality management system, especially in the area of quality control.

The above case explicitly confirms the importance of a solid quality management system for external services providers. Yet the existence of such system *per se* does not guarantee effective safety management, Beckmerhagen et al., [4]. Additional organizational actions are needed to promote strong safety culture.

Recent requirements for management systems have been further developed to integrate safety, health, environmental, security, quality and economic elements, IAEA, [8].

In the analysis of the supplemental personnel process description, INPO lists the following objectives and key attributes of the process that also promote high safety culture [12]:

- Supplemental personnel understand how significant the work they are performing is to nuclear safety and plant reliability. The technical competencies of supplemental personnel performing work for the plant are verified and appropriate for the task.
- Supplemental personnel exhibit proper industrial safety and human performance behaviours.
- Supplemental personnel know and understand that they are expected to stop and ask questions when unsure.
- Supplemental personnel understand the roles and responsibilities specific to the tasks they are performing.
- Service organizations and plant line managers clearly identify and reinforce accountabilities for supplemental personnel performance.
- Standards and expectations are thoroughly communicated to and understood by supplemental personnel.
- Responsibility for monitoring and oversight of supplemental personnel is identified clearly and performed effectively.
- An effective means of feedback exists that promotes continual improvement in supplemental personnel performance.

7 DEVELOPING AND MAINTAINING SAFETY CULTURE IN NUMIP

As the leading Slovenian nuclear services provider, NUMIP has been developing its safety culture in accordance with the guidelines from the previous chapters over many years. The fact that there is only one NPP in Slovenia, which limits the potential of involvement of personnel in nuclear services, resulted in the early decision of NUMIP to develop business in foreign NPPs. Currently, NUMIP crews carry out maintenance and modification services in NPPs in the USA and EU. Together with personnel from its subsidiary, Q Techna, NUMIP has been present at more than 30 different NPP units thus far. Lessons learned from different plants are very useful inputs for continual improvement programs.

A solid management system is a prerequisite for participation in the maintenance of NPPs, as well as for the development of a strong safety culture; therefore, NUMIP developed an integrated system in accordance with different requirements, including IAEA GS-R-3, IAEA, [8]. The management system is audited by our main customer and by global players on the nuclear market, who consequently place NUMIP on their Qualified Supplier Lists. The system is illustrated in Figure 2.

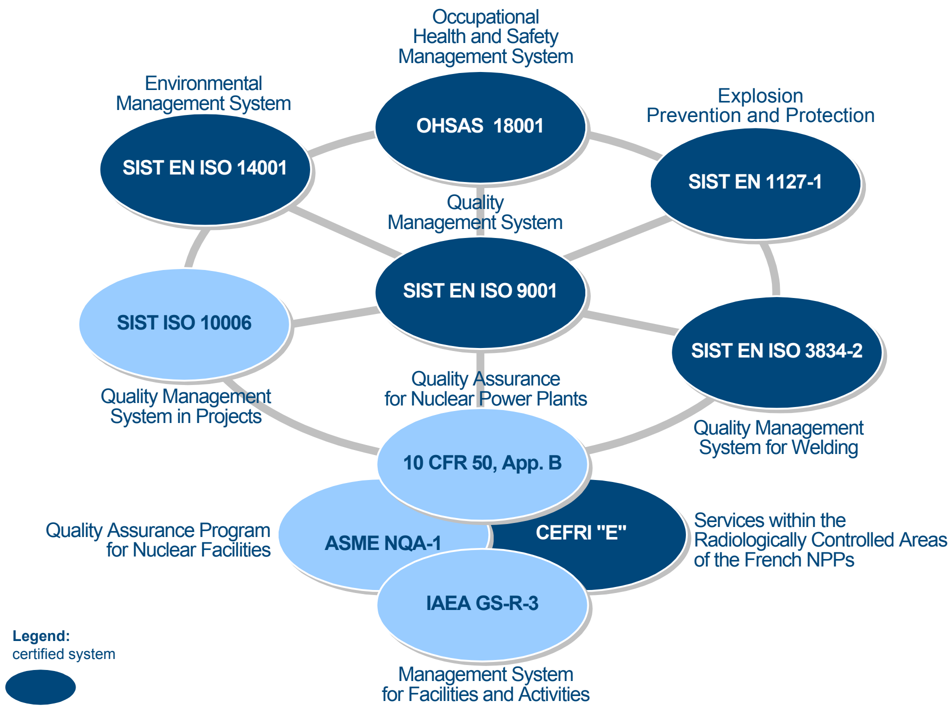

Figure 2: *Integrated management system of NUMIP d.o.o.*

Following the management system guidelines, education and training programs are developed that pay special attention to safety culture and to the good practices thereof. All internal trainings, including those for fitters and welders, contain guidelines for raising safety consciousness.

Applicable good practices are implemented to the extent possible, including human performance tools, INPO, [13], all with the objective of maintaining safety as a first priority of all workers and consequently of the organization as a whole.

Apart from implementation of the aforementioned management as well as the education and training system, the following practices are used in day-to-day activities:

- Pre-job briefing;
- Use of procedures and adherence with them;
- Open and clear communication;
- Self-checking;
- Different sorts of verifications;
- Questioning attitude;

- Use of lessons learned;
- Deployment of continual improvement and preventive/corrective action programs;
- Cooperation and teamwork;
- Shift overlap / detailed turnovers when working in shifts;
- Post-job review.

In almost 15 years of operation, NUMIP has recorded no major injuries of its personnel providing services in NPPs or impacts to plant safety or reliability. Given the fact that several hundred people are managed by NUMIP within complex outage projects, this is an achievement all employees are proud of. It confirms that the organization puts a great deal of emphasis on safety culture and it is determined to further develop it in the future.

8 CONCLUSION

Standards and criteria for the external maintenance services providers are the same as for the plant employees; therefore, the development and maintenance of safety culture is a great challenge for the external organizations. In some cases, those organizations do not have access to a sufficiently large nuclear market and need to work for other customers that may not be sensitive to safety culture. Consequently, these external services providers face a quite demanding task, as they need to establish and maintain a high level of safety culture even though they are not constantly involved in nuclear business. Understanding that "nuclear is different", it is very important for them to find as many opportunities for work in nuclear power plants as possible and thus maintain skills and safety consciousness. By following good practices and new developments in the nuclear field, external maintenance services providers should take responsibility to continuously develop the safety culture in their organizations and thus contribute to the safe and reliable operation of NPPs. In conclusion, the improvement of safety culture is a never-ending task for all parties involved in nuclear industry.

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BIOPLASTIC PACKAGING'S POTENTIAL AND ENERGY EFFICIENCY

POTENCIAL EMBALAŽE IZ BIOPLASTIKE IN ENERGIJSKA UČINKOVITOST

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Keywords: bioplastics, packaging, energy consumption

Abstract

The search for alternatives to petroleum-based plastics is multi-layered and motivated by various negative aspects, such pollution, toxicity, and difficult degradability, as well as issues regarding recycling, energy consumption, CO_2 emissions, and others. Since researchers and supply chains aim to evaluate the entire lifecycle of the production of goods, a wide range of materials are usually identified as potential substitutes to petroleum-based plastics, but when considering physical characteristics, bioplastics offer the most convenient replacement options. This article is a review the current state of its usage, and attempts to identify the approach that would make the adoption of bioplastics in packaging more viable, even though they are still in the early phases of development.

Povzetek

Iskanje alternativ petroplastiki je večplastno in je spodbujeno z mnogimi negativnimi vidiki, ki jih le-ta prinaša, kot so onesnaževanje, strupenost, težka razgradljivost, težave pri razgradnji, energetski porabi, emisijah CO2 in drugimi. Cilj raziskovalcev in oskrbnih verig je obravnavati celoten življenjski cikel proizvodnje dobrin, zaradi česar so kot potencialni substituti petroplastiki prepoznani mnogi različni materiali, vendar iz vidika fizikalnih lastnosti obeta

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najprimernejšo zamenjavo ravno bioplastika. Cilj članka je predstaviti trenutno stanje uporabe bioplastike in nato identificirati pristop, ki bi omogočil pospešitev oz. razširitev njene uporabe že v njeni sedanji, zgodnji fazi razvoja.

1 INTRODUCTION

Since 1856, when the first patent was granted to Alexander Parkes for the first manmade plastic, this material has fundamentally affected many aspects of modern civilisation to such a degree that it has become indispensable in countless production processes, and plastic goods are used in everyday life. In the beginning, plastics were made from the materials found directly in nature, and only in 1907 was the first synthetic plastic — known as "Bakelite" — developed, Meikle, [1]. At the time, the term "plastic" was still not defined precisely, and the U.S. Patent Office struggled to define this new category of materials, using various other terms instead, Freinkel, [2]. Bakelite was touted as "the material of a thousand uses", and its production greatly increased after the patent expired in the 1920s. In the following years, many new types of plastics were developed, and their proliferation increased even more after the World War II, especially in the period of cheap petroleum, Meikle, [1]. After the oil crisis of 1973 and the emergence of the awareness that the non-degradability of the plastics was causing increasing environmental problems, industry and researchers started to look for alternative sources of plastic feedstock beyond petroleum, and also diverted part of the development efforts toward the degradability and recyclability of plastics. Only in 1982 were the first truly biodegradable plastics developed, called "PHBV", marketed as "Biopol", Andrady, [3]. Although many more naturally derived feedstocks for plastic production have been developed since then, the major problem that still plagues the production of bioplastics is their comparatively more expensive manufacturing, overall economics, energy efficiency and substitutability with their petroleum-based counterparts. In the following two sections, the distinctive characteristics of the two types of plastics will be depicted, with the purpose of identifying the potential of bioplastics to generally substitute petroleum-based plastic material in packaging, which will be discussed in the following sections.

2 PETROLEUM-BASED PLASTICS

All types of plastic are actually polymers, of which there are three types: inorganic polymers, natural organic biopolymers and synthetic organic polymers. It should be emphasised that the great majority of the plastic produced today is based on petroleum feedstock and are synthetic organic polymers, Momani, [4]. Another important classification of plastics is into thermoplastics and thermo-set plastics, which has many direct implications regarding the physical characteristics, such as rigidity, remoulding capabilities and recycling procedures. Since petroleum-based plastic has evolved predominantly, it is also being produced in scores of varieties for number of application purposes. The most prominent amongst them are nylon, rayon, Kevlar, polyvinyl chloride (PVC), Lexan, polystyrene, polyethylene, and Plexiglas.

To put into perspective the pervasiveness and the ubiquity of the usage of plastics, it should be noted that 100 million tons of plastics are produced in the world annually, Wang et al, [5]; according to the data from 2004, more than 40% of the plastic consumption in Australia was due to packaging, HalveWaste, [6]. Other sources cite similar values, and consider packaging to be the biggest end use for plastics at 37%, followed by usage in building and construction at

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21%, automotive at 8%, and electric and electronic use at 6%, while medical, leisure and other applications consume 28% of the total plastic production, PlasticsEurope, [7]. According to Plastinum (2011), the total production of plastics in 2007 exceeded 260 million tons (different groups of materials are counted in this aggregated sum). Furthermore, the significant growth of plastic production began only after 1950, and was especially intensive in the last three decades, when the production surged ahead by more than 500%, while plastic consumption per capita reached 100 kg in North America and Western Europe, Plastinum, [8]. According to estimates, Momani, [4], petroleum-based plastics account for around 90–95% of total plastic production, while other assessments put it closer to 99%, HGCA, [9].

3 BIOPLASTICS

The remaining share of the plastic production is made from biomass feedstock, which results in bioplastic, Freinkel, [2]. The key difference is therefore only in the source of polymers that comprise this type of plastic, since they are not derived from petroleum, but from biomass sources, like vegetable fats, starch or microbes. These biopolymers can be produced either directly by an organism, or in a synthetic chemical reaction involving biological components. To avoid confusion, it should be pointed out that biodegradability ought not to be equated with bioplastics, considering that even certain types of petroleum-based plastic can be biodegradable, while the opposite is also true, i.e. there are also types of bioplastics that are not biodegradable, Stewart, [10]. Generally, however, bioplastics are usually more biodegradable than petroleum-based plastics. The next fact that should be taken into account is that the process of plastic production combines the constituent polymers with plasticisers, which enhance the pliability and other desired characteristics of the plastic. Plastics can also be made from biomass or from petroleum; their use generally does not depend on the type of the feedstock of the plastic, Momani, [4]. The characteristics of plastic, including biodegradability, toxicity, and others, are therefore also dependent on plasticisers.

The sources of biological feedstocks for bioplastics encompass plants such as wheat, potatoes, rice, corn, wood, soy, palm, or their sources can also be produced by bacteria. With the nascence of the genetic engineering, new possibilities have opened up for enhancements and modifications of the plants and bacteria used for production of those feedstocks, Luengo et al., [11]. Another new field of research with rising potential is nanotechnology, which is making important inroads in bioplastics. It promises to eliminate many of bioplastic's downsides, especially in regard to its physical properties, which are often not on a par with its petroleum-based counterparts, Lagaron and Lopez-Rubio, [12].

In the next section, we will compare the two types of plastics with the emphasis on their technological and other differences and their interdependencies in the markets.

4 COMPARISON

4.1 Petroleum consumption

As mentioned before, the overwhelming majority of plastics is based on petroleum, of which 4% of total world consumption is utilised directly as a feedstock for plastics, not counting the rest of the usage of petroleum that occurs at transportation, electricity and heat generation needed in

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the production and other parts of supply chain, Momani, [4]. Consequently, petroleum-based plastics account for significant usage of petroleum; however, the production of bioplastics also depends on it, although to a much lesser degree. A hypothetical significant shift of production from the petroleum-based plastics to bioplastics would therefore put pressure on oil prices, which would — all other things being equal —tend to decrease, thus lowering the cost of petroleum-based plastic production relatively much further in comparison to bioplastics.

4.2 CO_2 emissions

The net CO_2 emissions produced by supply chains for the purpose of production of plastics does not differ significantly regarding the transportation, heat and electricity production, etc., but much more so regarding the source of the feedstock and its obtainment. By extracting crude oil and converting it into plastic materials, the major part of the carbon remains in the material, but after its disposal, its degradation may cause the release of CO_2 into the atmosphere. The incineration of the plastics also releases CO_2 and although the produced heat can be useful, there are many pollution-related drawbacks. Nevertheless, this problem is not so severe with the incineration of bioplastics, since the carbon that is released stems from the biomass from which this plastic is produced. Therefore, the carbon was actually merely stored in the bioplastic, and its net contribution is negligible (when the rest of consumption, such transportation, heating, electricity, etc., is discounted).

4.3 Pollution

The many qualities that make plastics so useful and widespread, like durability, high temperature resistance, waterproofness, flexibility, etc., render them rather problematic once they are disposed of, since most of them do not degrade naturally and when they do, they may be toxic. This environmental issue is becoming especially troublesome with the continued growth of plastic usage, Mulder, [14]. In this aspect, bioplastic materials prove to be more environmentally friendly, although advances in making them more durable may deteriorate this characteristic significantly. There is one dominant advantage of plastics in comparison to many other materials, and this is their great potential for recycling. Technically, the operation itself is not complicated, since plastics can be easily reprocessed (for example, by melting at high temperatures, or by introduction of reactive chemicals). The obstacle to a greater adoption of recycling is that the collection and sorting of the plastics by their type makes the entire operation costlier than the production of new batch. To partially compensate for this disincentive, in many countries legislation was introduced that obliges producers to recycle discarded materials. This in turn forces them to rethink the usage of particular materials that are more difficult to reprocess, and to review the configuration of the product regarding the possibilities to reengineer it to make it more aligned with the more environmentally friendly standards.

4.4 Food production

One unprecedented dilemma that was introduced in the economic and social equation is that of the rivalry for land use, either for the cultivation of plants for food or for biomass. The dilemma

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is not so much one of efficiency, but instead a moral one. Due to increased production of corn and other crops for fossil fuel substitutes, the prices of those crops increased in the previous decade by as much as 25%. Since this food comprises the basic diet of poorer segments of the population, the question remains whether such an approach to obtaining biomass should be reversed or remodelled — and how either could be achieved. Petroleum-based plastic, however, does not raise such questions. The real problem in the background of these dilemmas is actually the recognition that shifting towards more environmentally friendly and sustainable economy and society might not be feasible without certain sacrifices.

4.5 Public health

When the regulators (state agencies and other similar organisations) allow certain materials to be used in the food, cosmetics and similar industries, where these materials directly or indirectly come in contact with people's bodies or are even being ingested by them, the regulators assume responsibility for public health. As a result, they must regularly perform various tests, especially on new materials, when their long-term effects are still not verified conclusively. Plastics certainly belong in this category of materials, and new findings regarding health issues should not come as a complete surprise. Due to those concerns, several types of plastics have been banned for usage in the food industry and other similar industries. The main source of health-risks at plastics comes from the fact that the polymerisation process might not be completely or sufficiently finished, which causes the polymers to continue to react with our cells, if we drink liquids or eat food that was packaged in such a plastic. This damages our cells and may cause various health issues like cancer. In this regard, bioplastics have proved to be much more "human-friendly". The feedstock from which they are produced is actually made from materials (e.g. starch, etc.) that our body is capable of processing, since they are of the same kind as our regular food. The only major downside can be the usage of pesticides, artificial fertilisers and other harmful chemicals that may be incorporated into the plastic packaging and finally transferred to its contents (like food or cosmetics).

4.6 Energy consumption

The production of plastics affects energy consumption in two ways. Firstly, the energy is used for the very process itself, encompassing feedstock production or extraction, reprocessing, transportation, the actual production, as well as marketing activities. Depending on the location of the production, the electricity can be produced by fossil fuels or by other means. Secondly, the production of petroleum-based plastics uses as its key ingredient the derivatives of crude oil, which could be otherwise used for generating energy, Daryl and Harvey, [14]. The estimate is that 4% of total oil consumption in 2008 was used as plastic feedstock; additional oil is also consumed for transportation and energy generation, Momani, [14]. The total energy input for plastics production is therefore estimated to be fifth after those for cement, steel, paper/board and bricks/tiles, Patel and Mutha, [15].

Any reduction in the usage of petroleum would therefore have an impact on total oil consumption. Since the consumption and production of plastics is growing annually by approximately 5.8%, Patel and Mutha, [15], the long-term predictions indicate that because that oil reserves are limited, changes will certainly be necessary in all areas of oil consumption. The

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depletion of oil sources will have two types of effects. Firstly, the quality of the extracted oil will deteriorate, thus the need for costlier and energy more demanding refinement process will be required to achieve the same level of output. Secondly, the more difficult sources of oil (in deep sea, or on a geologically more demanding terrain) will have to be tapped, thus further pushing the energy consumption and the prices up.

Additionally, it is reasonable to expect that in the coming years and decades more stringent limits will be passed regarding toxicity, pollution, recycling, CO_2 emissions, etc., thus further altering the current situation and the viability of production of different types of plastics.

Currently, the direct comparison of the petroleum-based plastics and bioplastics yields the conclusion that if the usage of petroleum for a feedstock of petroleum-based plastics is added to the total consumption of energy for the production, then the production of bioplastics indeed requires less fossil fuel, but the other factors still make it costlier or not feasible.

5 ECONOMICS

The market forces push its agents to optimise their participation in the production of all plastics, by constantly trying to lower the costs of their operations. The producers, for example, do not differentiate between the two alternative materials when they meet the required specifications of their physical properties, regardless of whether one of them is environmentally friendlier and the other is not. The main criterion they choose or are forced to use is the bottom line costs of the chosen materials. Actually, it is not only the producers that follow such optimisation principle — the same can be ascribed to entire supply chains and even final consumers. Of course, deviations might occur, since the market is fragmented, and certain segments of it have different levels of acceptable minimums. Nevertheless, trendsetting is usually dictated by the mainstream consumption.

From this standpoint, it can be concluded that bioplastics are vulnerable to the same pitfalls as other emergent technologies and corresponding industries. Older and more established alternatives usually prevent or throttle the newer technologies from developing or developing more rapidly. Older technologies have several key advantages that enable greater cost effectiveness: economies of scale, technologically more mature and optimised production processes, as well as robustly developed organisations and more stable and cheaper financing that support the production process.

On the other side, the many factors that determine the current optimums in favour of older technologies and materials, like petroleum-based plastics, will predictably change significantly in the future (as mentioned in the previous sections) or will no longer be acceptable by society due to their effects on health, pollution and other negative impacts.

The gradual upgrades of the technological processes in the supply chain also do not encourage its agents to commit themselves to the technologies that are not compatible with their existing equipment and support organisation, thus further delaying the wider acceptance of the new — and in the long term — more suitable technologies.

To break this inertia, governments are already stepping in with the introduction of legislation that either prohibits undesirable practices, materials or technologies completely, or changes their economics in such a way that it becomes more expensive in comparison with newer technologies, Coombs and Hall, [16]. Since such technologies are usually in their early phases of

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development, they cannot offer the same level of the output on the investment. This unavoidably leads to the higher prices of the produced materials — which is considered the price of the change that will have to be done eventually anyway.

The dilemma that legislators have is threefold. First, when is the right time to start enforcing the introduction of new technologies, so that the net effect in the longer term would actually be positive? Secondly, what is the possibility that the existing technologies evolve to such a degree to vastly diminish their main disadvantages, thus rendering their dismissal unnecessary? Finally, how can we cope with the new aspects that those emerging technologies would introduce? One example is the moral dilemma about substituting the production of food for biomass, causing basic food prices to increase, thus affecting the most vulnerable segment of the population.

In spite of the abovementioned questions, there is no doubt that government-induced changes in the business environment (especially by changing the costs of production) help those emergent technologies to develop much faster than they could under purely market conditions, Schwark, [17]. Since the majority of plastics production is dedicated for packaging, the advancements in this field could have the largest impact on the shift towards more environmentally and health-friendly bioplastic materials.

6 BIOPLASTIC PACKAGING

As previously, mentioned there are several reasons bioplastics offers superior advantages over petroleum-based plastics in the field of health, CO_2 emissions, etc., but those that are being sought the most are those that are impacting the producers’ profit margins. Since recycling is becoming increasingly required in various states, supply chains are trying to develop alternative concepts that would allow them to comply with such legislation, and are simultaneously seeking new optimums and cost-effectiveness of their operations. Their efforts are mainly in two directions: the producers try to make the recycling process cheaper to perform by developing strategies that permit cheaper recollection and sorting of discarded plastic, while they are simultaneously trying to avoid recycling altogether, by using biodegradable plastic materials. In this regard, bioplastics promise the most, since the end results of successful compost are only water, CO_2 and inorganic components without toxic elements, Siracusa et al., [18]. This characteristic makes disposing such bioplastic in the soil safe and harmless. The advantages of using bioplastic for food packaging are additionally beneficial, since they usually do not exhibit health risks, as they use polymers that human bodies can deal, with since they are similar or equal to those found in regular food.

There is another reason that makes the biodegradability a compelling quality of bioplastics, and that is the requirement of up to 99.9% purity of the many types of discarded bioplastics, which have to be free from certain petroleum-based elements, for recycling to be successfully performed, Hook, [19]. These facts indicate that further research and development is needed to be able to match the recyclability level of petroleum-based plastics. Similarly, its other characteristics will have to be matched as well, while many types of as plastic substitutes have yet to be developed, Coombs and Hall, [16].

Generally, plastics offer the following characteristics that make them economically attractive for packaging: low weight, good processability and no corrosion, Mulder, [13], as well as durability, strength, flexibility, visual aesthetic, and impermeability. These properties would be difficult or impossible to achieve with other known materials (such as paper, wood, metals, etc.).

PlasticsEurope, [7], estimates that 37% of plastics are used for packaging purposes; according to Shah et al., [20], this kind of plastic consumption grows at 12% rate per annum, surpassing the overall plastic consumption growth by approximately 6.2 percentage points. That would put the weight of plastic packaging currently at around 37 million tons (if we base the calculation on the conservative estimate of the total production of plastic of 100 million). Since there are 1.24 trillion barrels of known crude oil reserves, and in the 2008 the global daily consumption of the oil was 87.2 million barrels a day, this would mean that the world has approximately 36 years until those reserves would be depleted, at the current level of oil consumption. Although such predictions are not exact, they still forecast that society will have to endure drastic changes to overcome those facts — it is only a matter of time.

These trends suggest that the focus of development should be on plastic for packaging, since this would contribute the most to curbing down the overall consumption of the petroleum feedstock.

To illustrate the possibilities of remedying the increased petroleum consumption for plastics, we could use the PP (petroleum-based plastics) and PHB (bioplastics) as examples. The oil consumption to produce PP equals 73 MJ/kg, which consists of 58 MJ/kg worth of oil in the form of feedstock, and 15 MJ/kg in the form of energy, Gervet, [21]. In contrast, PHB requires 44.7 MJ/kg of energy to be produced, Momani, [4]. Other plastics offer varying levels of the energy usage, but overall the petroleum-based plastics generally use more oil than bioplastics.

7 CONCLUSION

The current state of affairs implies that the transition from petroleum-based plastics to bioplastics will have to be stepped up to diminish the much higher costs of a more sudden transition and adaption that might occur in the future if the suitable substitutes are not developed to a feasible degree. Certain inroads have been made in this field, but much more thorough and sophisticated regulation should be put in place by legislators to incentivise the market itself to invest in the development and research in this area, with as few negative consequences on food production, land use, etc. as possible. A general approach that focuses only on the end result of the production of plastic or energy consumption is not sufficient, since it consequently requires amendments to the original legal framework to correct the unwelcome anomalies that might have been predicted beforehand. The solution to this problem is the deeper discrimination of the specific energy and feedstock usages, as well as production technologies. The set of criteria that would be put in place should reflect the desirable priorities of the society, for example, that food production must be as much as possible independent from volatilities in the consumption of biomass made from the same crops. Such mechanisms require a more complex and more regulated approach to diverting resources in the right direction. Certainly, many assumptions that would lead regulators towards specific concepts of development might become obsolete and, consequently, the resources would not be employed optimally; generally, however, such an approach should yield better results, as has already been proven regarding current efforts in the field of recycling and others. Although the majority of oil extracted is currently used for transportation and energy production, specific utilisations — as is the example of production of petro plastics and explicitly its use in packaging — should not be neglected, especially taking into account the trends of recent decades. The successful development of the alternatives, of which bioplastics is the most promising, would significantly affect the overall consumption of oil and energy.

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CFD IMPLEMENTATION FOR PRACTICAL SIMULATION OF MULTIPHASE REACTIVE FLOW ON INDUSTRIAL SWIRL FLAME BURNERS

CFD UPORABA V PRAKTIČNIH SIMULACIJAH VEČFAZNEGA REAKTIVNEGA TOKA INDUSTRIJSKIH "SWIRLFLAME" GORILNIKIH

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Keywords: CFD, Multicomponent flow, Turbulent flow, Combustion, Industrial burner

Abstract

This paper investigates the characteristics of non-premixed combustion, carbon monoxide emission and flame geometry with a comparison of 18- and 22-MW NO_x reduced (NR) and swirl flame (1SF) burners mounted on a 20-MW hot water boiler on two essentially different fuel types. The simulated results indicate that with implementation of swirl technology, no unsteadiness of a flame burnout can be detected. Furthermore, the high mixing energy increases the reactive capability of a mixed phase on both the oil and gas fuels used in the process. With the increase of secondary air swirl strength, the flamelet or jet area tends to be greater, and the circular flow of high temperature flow gas is enhanced. The flame tends to be shorter and wider. However, the capability to adjust a 1SF burner to different boiler geometries is closely combined with flame stabilization and flue gas emissions; therefore, the right flame geometry is determined by various CO emissions throughout flame region. With turbulence intensity, the flame length was reduced by approximately 55% without a loss of reactive

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stability. As for the increased swirl ratio, a recirculation flow in flame core also increases parallel to it, thereby reducing the flame core temperature, hence decreasing the thermal NO_x build.

Povzetek

Ta članek se osredotoča na raziskavo ne-predmešanega zgorevanja, emisije ogljikovega monoksida ter geometrijo plamena z uporabo dveh v osnovi različnih gorilniških izvedb. Izvedba NR ter 1SF (“swirlflame”) na dveh neodvisnih toplotnih kapacitetah (18MW in 22 MW) ter dveh vrstah goriva (KOEL, zemeljski plin). Rezultati simulacije kažejo, da je z uporabo vrtinčne tehnologije mogoče skoraj popolnoma odpraviti nestabilnosti pri tvorbi plamena. Visoka energija mešanja povečuje reaktivnost mešane faze tako z uporabo KOEL kot ob delovanju na zemeljski plin. Z dvigom vrtinčnega indeksa sekundarnega vpiha zraka se poveča premer plamena, hkrati pa tudi intenzivnost interne recirkulacije dimnih plinov. Plamen je tako krajši in širši. Možnost uporabe gorilnika 1SF na različnih kuriščih je v tesni povezavi s stabilizacijo plamena in emisijami dimnih plinov, saj je informacija o prisotnosti plamena (tudi nevidnega dela) vezana na spremenljivo emisijo CO po celotnem plamenskem področju (plamen je prisoten dokler še poteka oksidacija). Z uporabo vrtinčne tehnologije je mogoče brez izgube stabilnosti plamen skrajšati za ca. 55%. Hkrati s povečanim vrtinčnim učinkom pa se poveča tudi stopnja recirkulacije dimnih plinov v jedro plamena, kar močno vpliva na zmanjšanje nastanka termičnih dušikovih oksidov (NOx).

1 INTRODUCTION

At present, the process of developing new burner designs is limited to known base designs, the known aero-dynamical properties of standard burners and, most importantly, the unknown behaviour of the burner on its power range.

Since the introduction of commercial digital burner control about a decade ago, nothing “revolutionary” has happened in the development of new, more efficient burners, without a great cost input. A modern industrial burner should handle a high efficiency rate, meet ecological requirements and provide steady, safe operations in extreme conditions.

Linked to the fact that it is fiscally inefficient to test every burner generation type on every industrial boiler, to some degree burners are subjected to every known form of field testing, which is combined with the process of creating a harsh environment, technological or process blunders and even intentional damage to test safety procedures. All of which are drains on manufacturer’s resources and takes time.

With the implementation of CFD technology, all of the aforementioned can be done using a standard numerical tool combined with an adequate mathematical model for selecting the correct option.

In this paper, the combustion process is studied with 18- and 22-MW NO_x reduced and swirl flame industrial burner comparison.

With burners mounted on a 20-MW hot water boiler, the characteristics of non-premixed combustion, carbon monoxide emission and flame geometry are investigated with conclusions providing evidence for practical operation.

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2 METHODS

In this study, numerous methods were implemented. Building a flexible mathematical model for practical use is based on an experimental method of measuring flame geometry by linking combustion theory with practical emission results.

The main focus of the geometry study was the CO emission combined with a turbulent flow of mono-component fluid (gas burner type SF) and turbulent flow of multicomponent flow (oil burner type SF). There were total of 50 various simulations on various meshes.

The main criterion was the use of continuum equations for the basis of a steady flow model, later upgraded to turbulent reactive flow [1]. The important question was which mathematical model to use in combination with a CFD tool to obtain approximately the same results as with experimental methods [2].

Experimental results were measured at the Max Weishaupt development institute in Schwendi, Germany. The primary burner generation used was WKGL 80 type 1SF and NR, both at 18 and 22 MW.

2.1 Physical model

There is one burner installed on the boiler's front wall. The boiler is a 20-MW hot water boiler, providing a load capacity up to 22 MW of burner output power. It is three-pass type, shown in Figure 1.

Figure 1: *Three-pass hot water boiler*

The NR burner mixing chamber shown in Figure 2 is a NO_x reduced type of burner with Class 3 NO_x emission with natural gas combustion and Class 1 NO_x emission with oil combustion, both corresponding to EN267. In comparison to an NR type with a traditional gas or oil burner, the NR emits very low concentrations of NO_x and is widely used in all new industrial applications.

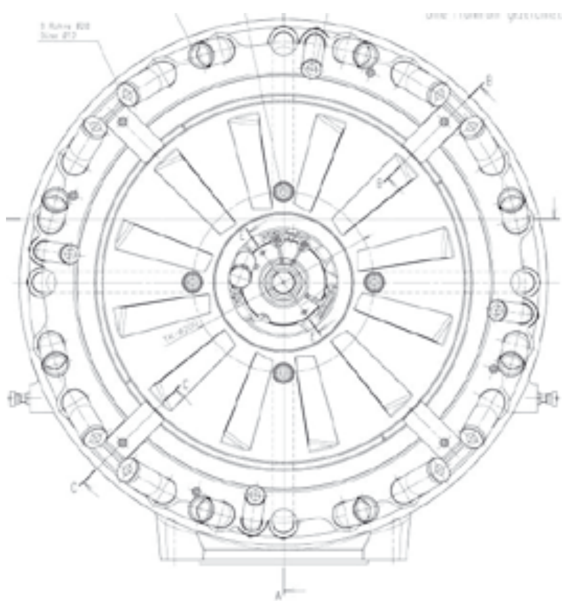

Figure 2: *NR burner mixing chamber*

As shown in Figure 2, the primary air inlet at the burner central zone is filled with an oil distribution system (oil nozzle). The primary air is evenly distributed on a turbulent-type plate to enable rotary (but not swirl) air distribution throughout combustion chamber. Secondary air is distributed between turbulent type plate and the outer ring filled with gas fuel inlets; it builds flame geometry along with appropriate mixing energy. Although there are two different fuel type inlets, the burner is not capable of simultaneous combustion with installed equipment. The flame is usually sleek, long and with a small diameter. As a conventional burner type, the flame geometry corresponds to most known types of industrial boilers with the goal of achieving maximal volume heat load throughout a boiler combustion chamber.

In contrast, there are some specialties on some industrial applications. The use of water tube boilers is not as significant as it was in the mid-20th century, but when a high energy capacity is needed from one block boiler, this is the only choice. Water tube boilers tend to use a very short and wide diameter combustion chamber. Normally, there are several burners installed on one boiler, all with the same load capacity. The problem is that conventional burner types cannot handle such combustion chamber geometry without direct physical contact with a boiler heat exchanger, so the method with a swirl flame burner is used.

The swirl flame mixing chamber in Figure 3 is essentially a high energy mixer.

Figure 3: *1SF burner mixing chamber*

The primary air inlet consists of two swirl turbulent type plates, providing high energy rotary movement of the central primary air and stable rotary air movement on the middle ring. The secondary air has same function as with the NR-type burner mentioned above.

2.2 Mathematical model

This paper adopts *k*-ε two equation model to simulate one-phase and two-phase flow of fluid (we assume natural gas and air as one phase flow) and mixture fraction for fuel/oxidizer rate. Gas turbulence and CO emission are included, because CO emission is a good flame length indicator (there are still chemical combustion processes on the flame tip although there is no longer a visible flame).

The software consists of an Eulerian calculation for flow field and a Lagrangian calculation about temperature and combustion process.

The mesh adopts an asymmetric grid since the primary interest is over burner level and not on the the boundary regions of the boiler.

Mixture fraction is based according to equation 2.1,

$$\frac{\partial \bar{\rho}\tilde{z}}{\partial t} + \nabla\left(\bar{\rho}\tilde{\vec{V}}\tilde{z}\right) = \nabla\left[\frac{\mu_t}{\sigma_t}\nabla\tilde{z}\right] \tag{2.1}$$

and turbulence intensity in equation 2.2,

$$I = \sqrt{\overline{f'^2}} \Big/ \bar{f} \qquad 2.2$$

where *I* is ratio between mean fluctuating contribution and mean turbulence contribution.

3 RESULTS AND DISCUSSION

The main goal was to test the current mixing geometry on industrial burners and to develop a software model for future development use.

Since the main application of the SF burner type is on water-tube boilers with limited combustion chamber length, the primary goal was to shorten the flame length up to 50% without an intensive increase of the main combustion pollutants (NO_x, CO).

In order to discuss the influence on combustion by burner load, this paper examines two different loads: one with 18-MW burner output and the other with 22-MW burner output. For the 18-MW output, the inlet air pressure on the non-premixed side of mixing chamber is around 50 mbar on each of burner type.

Primary air swirl ratio according to secondary air inlet was 78% in both load and fuel cases.

Figure 4 shows that, according to standard flame geometry of NR burner type (upper case), 1SF reduces flame length up to 50% without output power loss. Carbon monoxide emissions are lower in flame root in comparison to NR significantly. This phenomenon is based on the better mixture ration of the 1SF burner, thereby yielding the higher oxidation intensity of CO to CO_2. As mentioned before, flame length is characterized by chemical kinetic; therefore, the NR flame tip (invisible to human eye) reaches to the end of combustion chamber. 1SF produces a much shorter and wider flame geometry. Carbon monoxide emissions are reduced according to experimental results: in 40% of the combustion chamber length, there is essentially no longer any reaction flow.

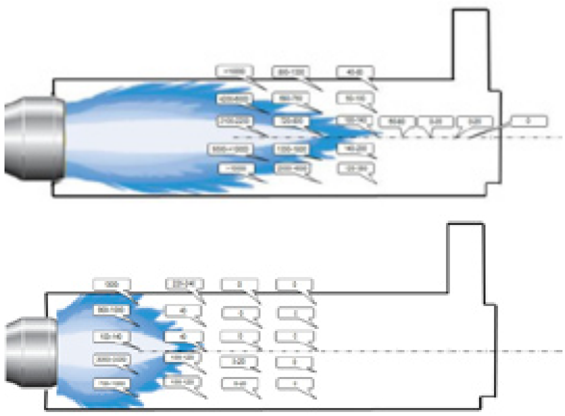

Figure 4: *NR and 1SF comparison on 18 MW burner power – fuel GAS with CO emission*

As a load enhancement, Figure 5 shows the different flame geometry on a 22-MW NR and 22-MW 1SF gas burner type.

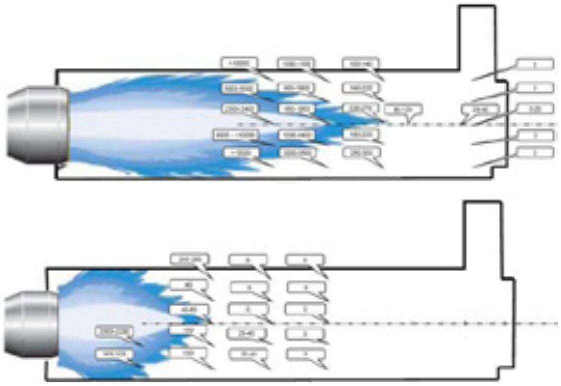

Figure 5: *NR and 1SF comparison on 22 MW burner power – fuel GAS with CO emission*

As mentioned for the 18-MW case, the same phenomenon can be observed here with even better CO results. Since the boiler has a 20-MW capacity, and a combustion efficiency of approximately 91%, the burner load of 22 MW is more suitable for an industrial application, according to its better volume load ratio.

Here, the thermo-acoustic phenomenon was taken derived from another study [3], since the equipment for experimental measurement is very expensive.

As mentioned before, the basis for the steady flow was a conservative formulation [4]. For the gas burner, a simplified flow with one component was used, since the natural gas-air mixture can be simplified as one component with a less than 5% error at convergence. Flow simulation was initially incompressible; for later research, the simulation will be real-time compressible.

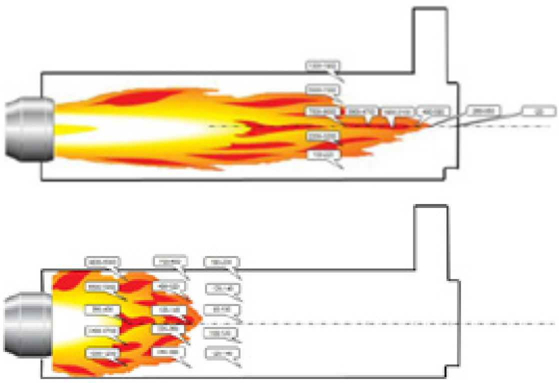

Figure 6: *NR and 1SF comparison on 18 MW burner power – fuel OIL with CO emission*

Zone models [5] were used to control volume distribution. As for the oil burners in Figure 6, a test was made with the PDF model. The oil burner simulation is based on multicomponent flow with one component as compressible fluid (air) and one incompressible (oil). As in the gas-fuelled cases, the swirl phenomenon is also applied for the oil case. With a slightly lower mixture ratio of atomized oil drops and air, the CO emissions are significantly higher on NR, but strongly damped on the 1SF type. As with the 22-MW gas-fuelled example, so is the case with

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22-MW oil-fuelled burner: volume load in combustion chamber has a strong influence on the reactive flow, regardless of the reactive mixture inertia.

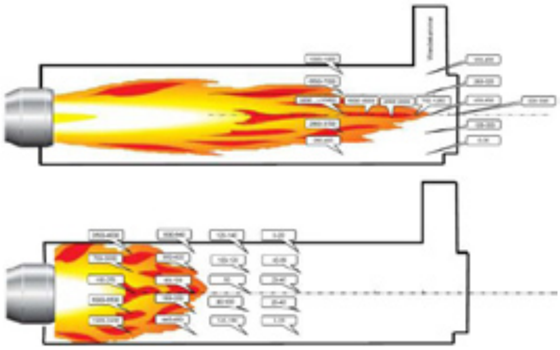

Figure 7: *NR and 1SF comparison on 22 MW burner power – fuel OIL with CO emission*

With implementation of real fluid models, the rate of convergence [6] increased with every new simulation. Since no geometry change of the mixing chamber was made, the results are based only on comparison with experimental results.

4 CONCLUSION

The practical use of the model will be tested with the new generation of SF burners. In fact, there is no practical way of non-field burner testing at 22 MW power and higher; therefore, the model will find its use as a cost- and time-efficient way of developing energy efficient and ecologically acceptable industrial burners of the future.

The stability of reactive flow can be sustained up to ca. 50% of turbulence intensity; that permits shortening of flame length by approximately 55%. The increase of turbulence intensity causes strong instabilities in both flow field and reactive layer. At critical pressure ratios, the flame drops out and that burner is at fault status. In contrast, swirl ratios under 50% cause a flame and swirl plate contact, which increases CO emission, creates thermal erosion and disrupts flame geometry.

As for increased swirl ratio, parallel to it the recirculation flow in flame core also increases; therefore, the flame core temperature reduces, hence decreasing the thermal NO_x build.

Swirl flame type burners have been shown to be a more efficient way for industrial applications on short-scale boilers than typical burners. Of course, this does not mean that conventional burner types are obsolete for modern combustion applications. In the end, the only desirable effect is the right heat volume load parallel with high efficiency rates and low operation costs.

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FUZZY DYNAMIC LINEAR PROGRAMMING IN ENERGY SUPPLY PLANNING

MEHKO DINAMIČNO LINEARNO PROGRAMIRANJE PRI NAČRTOVANJU ENERGETSKE OSKRBE

Janez Usenik[ℜ]

Keywords: dynamic linear programming, fuzzy linear programming, fuzzy dynamic linear programming, energy system.

Abstract

Linear programming is an important field of optimisation. Many practical problems can be expressed as linear programming problems and be solved with a simplex method. When all data in a linear program are determined and quantities are known in advance, the simplex algorithm, i.e. the simplex method, is explicit. However, in special cases the coefficients in the linear programming problem can be a) fuzzy numbers or b) functions of time with specific requests. In this manner, we have either fuzzy linear programming in the first situation or continuous dynamic linear programming in the second. The synthesis of both methods is a fuzzy dynamic linear programming problem, which is explored in this article and represents a new method in the theory of linear programming problems. Following the theory, we have some different procedures for solving an energy supply planning problem, Fabijan, Predin, [1], Usenik, [2]. One rational possibility is to define the mathematical model as a problem of fuzzy dynamic linear programming and solve it with the new simplex procedure. In this article, the simplex method for this possibility is proposed. At the end of the article, a numerical example is shown.

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Povzetek

Linearno programiranje je pomembno področje optimiranja. Veliko praktičnih problemov je mogoče izraziti v obliki linearnega programa, ki ga nato rešujemo s simpleksno metodo. Ko so spremenljivke in vsi koeficienti linearnega programa konstante, je algoritem, to je metoda simpleksov, jasen in znan. V posebnih primerih pa so spremenljivke in koeficienti lahko a) mehka števila ali b) časovne funkcije, ki zadoščajo posebnim zahtevam. V prvem primeru govorimo o mehkem linearnem programiranju, v drugem pa o zveznem dinamičnem linearnem programiranju. Sinteza obeh možnosti pa je mehko dinamično linearno programiranje, ki ga prikazujemo v tem članku in prestavlja pomembno novost v teoriji linearnega programiranja. Problem energetskega načrtovanja je mogoče rešiti na več načinov, Fabijan in Predin [1], Usenik [2]. Ena od racionalnih možnosti je, da matematični model upravljanja sistema zapišemo kot problem mehkega dinamičnega linearnega programa in ga rešimo z novo simpleksno metodo. V članku je definiran in uporabljen simpleksni postopek za to možnost. Dodan je še numerični primer, ki ilustrira vse algoritme.

1 INTRODUCTION

Linear programming is the optimisation technique most frequently applied in real world problems. Any linear programming model representing real situations involves many variables whose values are assigned by experts. In the conventional approach, experts are required to fix an exact value for the variables. However, in many cases, the coefficients involved in the objective function and in constraints are not well-known quantities, and frequently we do not precisely know the values of those parameters. In this way, the knowledge of experts about the variables is presented in two different ways: a) to represent the variables as functions of time in this case, we are talking about the dynamic linear programming problem (DLP), developed by Rupnik, [3], [4] and Usenik, [5], [6], or b) as fuzzy data permitting fuzzy linear programming (FLP), developed first by Zimmermann, [7] and afterwards by many other authors [8], [9], [10], [11].
The simplex method is a basic and well-known procedure for solving problems in the theory of linear programming, developed by Dantzig [12]. The simplex method for both possibilities (DLP and FLP) is generally the same, but all modifications for dynamic and for fuzzy data must be taken into consideration.

2 DYNAMIC LINEAR PROGRAMMING

In the problem of linear programming (LP) in the general form, Dantzig, [12]

$$\begin{aligned} &opt \quad z=(c,x) \\ &\text{s.t.} \quad Ax=b \\ &\qquad\ \ x\geq 0 \\ &c,x\in R^n, b\in R^m, A\in R^{m\times n} \end{aligned} \tag{2.1}$$

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some modifications are made. First, we change all constant vectors by vector functions in a finite interval of time $[0,T], T<+\infty$ so that functions depend on explicit restrictions and belong to the classes R_X, R_A, R_b, R_c, i.e. $b(t)\in R_b$, $c(t)\in R_c$, $x(t)\in R_X$ and $A(t)\in R_A$. The functions from the classes R_b, R_c, R_X and R_A are continuous and at least once-derived real functions. Functions from R_b are still non-negative and functions from R_A are monotonously limited and only finitely many times non-finite real functions. With these completions, we have now the problem called the "continuous variable dynamic linear programme", developed by Rupnik, [3], and Usenik, [5]:

$$\begin{aligned} &opt \quad z(t)=[c(t),x(t)] \\ &s.t. \quad A(t)x(t)=b(t) \\ &\qquad\quad x(t)\geq 0 \end{aligned} \tag{2.2}$$

Then the matrix $A(t)$ is divided into two parts: $A(t)=\left[A_0(t)\vdots\tilde{A}(t)\right]$. All the elements of the first submatrix $A_0(t)$ are known finite real functions and belong to the class R_A, whereas all the elements of the second submatrix $\tilde{A}(t)$, $\tilde{A}(t)=\left[\hat{P}_{\mu+1}(t)\ \ \hat{P}_{\mu+2}(t)\ \ \cdots\ \ \hat{P}_n(t)\right]$ are unknown finite real functions from the class R_A, but are convexly linked in columns $\hat{P}_j(t)\in C_j(t)$ for all $j=\mu+1,\mu+2,\ldots,n$, $1<\mu<n$. In this case, we arrive at the problem called "generalised continuous variable dynamic linear programming", developed by Usenik, [5], [6]:

$$\begin{aligned} &opt \quad [c(t),x(t)] \\ &s.t. \quad \left[A_0(t)\vdots\tilde{A}(t)\right]x(t)=b(t) \\ &\qquad\quad x(t)\geq 0, \\ &\qquad\quad \hat{P}_j(t)\in C_j(t), \\ &\qquad\quad j=\mu+1,\mu+2,\ldots,n \end{aligned} \tag{2.3}$$

To set up the algorithm and prove the existence of the solution as well as the optimum method of calculating this problem, we use a step-by-step approach and calculate the following three subproblems ($t\in[0,T], T<\infty$):

if $A(t)=A(0)$, $c(t)=c(0)$, then we have the subproblem called <u>b-CDLP</u>

$$\begin{aligned} &opt \quad [c(0),x(t)] \\ &s.t. \quad A(0)x(t)=b(t) \\ &\qquad\quad x(t)\geq 0 \end{aligned} \tag{2.4}$$

if $A(t)=A(0)$, $b(t)=b(0)$, then we have the subproblem called <u>c-CDLP</u>

$$\begin{aligned} &opt \quad [c(t),x(t)] \\ &s.t. \quad A(0)x(t)=b(0) \\ &\qquad\quad x(t)\geq 0 \end{aligned} \tag{2.5}$$

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if $A(t)=A(0)$, then we have the subproblem called c/b-CDLP

$$\begin{aligned} & opt \quad \left[c(t),x(t)\right] \\ & s.t. \quad A(0)x(t)=b(t) \\ & \qquad x(t)\geq 0 \end{aligned} \tag{2.6}$$

Programs (2.4) and (2.5) are solved by Rupnik [3], program (2.6) by Usenik [5].

2.1 Simplex method for CDLP problem

If we mark the union of areas of admissibility of k-th solution with M_k, and the union of areas of structural constancy of the base of k-th solution with $\left[SS\right]_k$, we can prove, Rupnik [4], Usenik [5]:

Theorem 1: *If the following conditions are fulfilled*

a) $b^{(0)}_{r^{(0)}_{\{\tau_0\}},s^{(0)}_{\{\tau_0\}}}(t)\geq 0, t\in\left[0,T\right]$,

b) $a^{(p-1)}_{i,s^{(p-1)}_{\{\tau_{p-1}\}}}(t)>0$,

c) $\overline{c}^{(p-1)}_j(t)<0$,

for at least one $i\in\{1,2,\ldots,m\}$ *and at least one nonbasic* $j=s^{(p-1)}_{\{\tau_{p-1}\}}$, $p=1,2,\ldots,k$ *, then for the problem (2.2) in the non-empty area* $\mathrm{M}_k\cap\left[\mathrm{SS}\right]_k\subseteq\left[0,T\right]$ *one segmentally structurally stationary feasible basic solution* $x^{(k)}(t)\in R_b$ *exists.*

Under the conditions of Theorem 1, we can always obtain the structurally stationary basic solution $x^{k_0(t)}$ of problem (2.2). In further study of the basic problem, we discover that the above solution of the problem is only one of the several feasible basic solutions defined in the separate subinterval of the basic interval $\left[0,T\right]$. For the basic problem (2.2), this solution is structurally stationary but certainly not yet optimum. The existence of optimal solution is found in the Theorem 2 (see proof in Usenik, [5]).

Theorem 2: *If the following conditions are fulfilled*

a) $b^{(0)}(t)\geq 0, t\in\left[0,T\right]$,

b) $a^{(p-1)}_{i,s^{(p-1)}_{\{\tau_{p-1}\}}}(t)>0$ *for at least one* $i\in\{1,2,\ldots,m\}$ *and* $p=1,2,\ldots,k_0$,

c) $\overline{c}^{(p-1)}_j(t)<0$ *for at least one nonbasic* $j=s^{(p-1)}_{\{\tau_{p-1}\}}$ *and* $p=1,2,\ldots,k_0$,

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d) $\bar{c}_j^{(k_0)}(t) \geq 0$ *for all* $j \in \{1,2,\ldots,n\}$,

where $k_0 = k_0(t) \in N$ *is the finite number for every* $t \in \mathrm{M}_{k_0} \cap [\mathrm{SS}]_{k_0} \subseteq [0,T]$, *then for the problem (2.2) in the non-empty area* $\mathrm{M}_{k_0} \cap [\mathrm{SS}]_{k_0} \subseteq [0,T]$ *one non-trivial optimal segmentally structurally stationary feasible basic solution* $x^{(k_0)}(t) \in R_b$ *exists in the form*

$$\begin{aligned} & x^{(k_0)}(t) = \left[P^{(k_0)}_{\{\tau_{k_0}\}}(t) \right]^{-1} \cdot b^{(0)}(t) \\ & t \in \delta^{(k_0)}_{\tau_{k_0}}, \tau_{k_0} = 1,2,\ldots,g_{k_0}\left(\tau_1, \tau_2, \ldots, \tau_{k_0-1}\right) \end{aligned} \qquad (2.7)$$

in the intervals $\delta^{(k_0)}_{\tau_{k_0}}, \tau_{k_0} = 1,2,\ldots,g_{k_0}\left(\tau_1,\tau_2,\ldots,\tau_{k_0-1}\right)$, $\bigcup_{\tau_1=1}^{g_1} \bigcup_{\tau_2=1}^{g_2} \cdots \bigcup_{\tau_{k_0}=1}^{g_{k_0}} \delta^{(k_0)}_{\tau_{k_0}} = \mathrm{M}_{k_0} \cap [\mathrm{SS}]_{k_0}$

Now the following is true: programme c/b/A – CDLP has a finite number of iteration steps (Theorem 1); under conditions of Theorem 2, separate subprograms are all type c/b-CDLP and also have a finite number of iteration steps; the vectors $\hat{P}_j(t)$ are either extreme points of convex polyhedrons or a linear combination of these points. If convex polyhedrons have a finite number of extreme points, we can see that in this case the number of iteration steps is finite.

Theorem 3: *If the following conditions are fulfilled*

1. for the existence of the optimum solution c/b/A-CDLP the conditions of theorem 1,

2. elements $a^{(p-1)}_{r^{(p-1)}_{\{\tau_{p-1}\}}, s^{(p)}_{\tau_p}}$ *are strictly positive for* $p = 1,2,\ldots,k_0$,

3. convex polyhedrons have a finite number of extreme points, then there is an optimum solution of the problem c/b CDLP (2.6) in a non-empty segment of the time interval.

2.2 Simplex method for GCDLP problem

Generalised continuous variable dynamic linear programming problem (2.3) can be solved in two phases. During Phase 1, we are calculating the problem (2.2), i.e. CDLP. In Phase 2, the optimal solution of Phase 1 ought to be improved by additional optimisation of the structure of all vectors $\hat{P}_j(t)$, $j = \mu+1, \mu+2, \ldots, n$, $1 < \mu < n$ under convex restriction. In this way, we obtain the optimum solution of the basic problem (2.3), which is now called *the main programme* in the general algorithmic structure**.**

The optimum solution of Phase 1 (CDLP) is defined as initially feasible solution of the problem (2.3) ${}^{(1)}x^{(k_0)}(t) = {}^{(2)}x^{(0)}(t)$ in separate subintervals $\delta^{k_0}_{\tau_{k_0}}$ into which the basic interval $[0,T]$ broke up during the calculations of Phase 1. From this initial solution, we calculate the first feasible basic solution of the second phase ${}^{(2)}x^{(1)}(t)$ as a structurally stationary solution for separate time intervals, then the second one, the third one, etc.

Suppose we obtain a structurally stationary feasible basic solution ${}^{(2)}x^{(k-1)}(t)$ in all subintervals $\xi_i^{(k-1)}$. A structurally stationary constant basis $\hat{\mathrm{L}}^{(k-1)}$ and its corresponding inverse $\left[\hat{\mathrm{L}}^{(k-1)}\right]^{-1}$ belong to the solution in separate subintervals. In the inverse of this basis, elements in the last line are the simplex multiplicators ${}^{(i)}\pi^{(k-1)}(t), i=1,2,\ldots,p_{k-1}$. By the definition of the simplex method, Dantzig [12], we have

$$\begin{aligned}
&{}^{(i)}\hat{\pi}^{(k-1)}(t).\hat{P}_j(t)\geq 0\\
&\text{for } j=1,2,\ldots,\mu\\
&{}^{(i)}\hat{\pi}^{(k-1)}(t).\hat{P}_j(t)=0 \quad \text{for basic } j\in\{1,2,...,n\}\\
&{}^{(i)}\hat{\pi}^{(k-1)}(t)\hat{P}_0(t)=1\\
&{}^{(i)}\hat{\pi}^{(k-1)}(t).\hat{P}_j(t)<0 \quad \text{for nonbasic } j\in\{\mu+1,\mu+2,\ldots,n\}\\
&t\in\zeta_i^{(k-1)}, i=1,2,\ldots,p_{k-1}
\end{aligned} \tag{2.8}$$

and therefore k-th solution is derived from (k-1)-th solution if we manage to solve the system of k-th subprogrammes in all the subintervals $\zeta_i^{(k-1)}, i=1,2,\ldots,p_{k-1}$.

$$\begin{aligned}
&\min {}^{(i)}\hat{\pi}^{(k-1)}(t)\cdot\hat{P}_j^{(k-1)}(t)\\
&\hat{P}_j^{(k-1)}(t)\in C_j \quad \textit{for } j\in\{1,2,\ldots,n\}\setminus I_2\\
\\
&\min {}^{(i)}\hat{\pi}^{(k-1)}(t)\cdot\hat{Q}_{s_j}^{(k)}(t)\\
&\hat{Q}_{s_j}^{(k)}(t)\in C_{s_j}(t) \quad \textit{for } s_j\in I_2\\
&t\in\zeta_i^{(k-1)}, i=1,2,\ldots,p_{k-1}
\end{aligned} \tag{2.9}$$

As the complex polyhedrons are defined by the system:

$$\begin{aligned}
&\sum_{i=1}^{m+1}\alpha_{ijk}\tilde{a}_{ij}(t)\leq d_{jk}(t)\\
&j=\mu+1,\ldots,n;\; k=1,2,\ldots,p_j
\end{aligned} \tag{2.10}$$

then (2.9) represents the system of CDLP, if the following is true:

$$\begin{aligned}
&d(t)\in R_b,\; d(t)\geq 0\\
&{}^{(i)}\hat{\pi}^{(k-1)}(t)\in R_c,\; \tilde{a}_{ij}(t)\in X
\end{aligned}$$

Theorem 4: *For* $c_j^{(0)}(t)\in R_c$ *and strictly positive elements* $a^{(p-1)}_{r^{(p-1)}_{\{\tau_{p-1}\}},s^{(p)}_{\tau_p}}(t)\in R_c$, $p=1,2,\ldots,k_0$ *calculating c/b/A-CDLP and for strictly positive* $\tilde{a}^{(q-1)}_{r,s_q}(t)$, $q=1,2,\ldots,k$, *the systems of q-th subprograms are the problems of c/b-CDLP´s type.*

From Theorem 4, we can see that further subdivision of subinterval $\xi_i^{(k-1)}$ takes place. In general, during the process of calculating r-th c/b-CDLP, the h-th subinterval can break up into subintervals ${}_{(r)}\Delta_{h,1}^{(k-1)}, {}_{(r)}\Delta_{h,2}^{(k-1)}, \ldots, {}_{(r)}\Delta_{h,\rho_h}^{(k-1)}$ with the following solutions:

$$\begin{aligned} &{}^{(h)}\pi^{(k-1)}(t) \cdot \hat{P}_{r,1}^{\{k\}}(t) \in {}_{(r)}\Delta_{h,1}^{(k-1)} \\ &\quad \ldots\ldots \\ &\quad \ldots\ldots \\ &{}^{(h)}\pi^{(k-1)}(t) \cdot \hat{P}_{r,\rho_k}^{(k)}(t) \in {}_{(r)}\Delta_{h,\rho_k}^{(k-1)} \end{aligned} \tag{2.11}$$

For the purpose of further optimisation in the main programme these solutions must be negative.

Theorem 5: *Under conditions for the existence of optimum solution c/b/A-CDLP and under conditions of Theorem 4, there is k-th feasible basic solution that is structurally stationary in separate subintervals of the* ${}_{(r)}\Delta_{h,1}^{(k-1)}, {}_{(r)}\Delta_{h,2}^{(k-1)}, \ldots, {}_{(r)}\Delta_{h,\rho_h}^{(k-1)}$ *type.*

During further subdivision of subintervals $\zeta_i^{(k-1)}$, $i = 1,2,\ldots,p_{k-1}$ subintervals ${}_{(z)}\Delta_{i,\rho_k}^{(k-1)}$, $z = 1,2,\ldots,n-\mu$ are generally not the same. For this reason, separate solutions are compared by means of the definite integral in every $\zeta_i^{(k-1)}$ by establishing *the criterion for the selection of the input vector* into the basis of the main programme:

$$\min_j \left[\sum_{i=1}^{\kappa_k} \int_{t_{i-1}}^{t_i} {}^{(h)}\hat{\pi}^{(k-1)}(t) \hat{P}_{j,i}^{(k)}(t) dt \right], j \in \{\mu+1, \mu+2, \ldots, n\} \tag{2.12}$$

As the solution of k-th subprogrammes for $t \in \zeta_i^{(k-1)}$ must be monotonous, we introduce other additional conditions (2.2). When we have monotonously selected the index of the input vector for the main programme, there are two possibilities:

The minimum of the average solution in the entire $\zeta_i^{(k-1)}, i = 1,2,\ldots,p_{k-1}$, is the one with the index s_k, while the vector with this index is not yet in the basis. In this case, the vector $\hat{P}_{s_k}^{(k)}(t)$ enters the basis at $\zeta_i^{(k-1)}$. Because it is possible that the convex polyhedron $C_{s_k}(t)$ may not have been completely exploited, we have to make an allowance for the variation of this vector:

$$\begin{aligned} &\hat{P}_{s_k}(t) = \left[\hat{P}_{s_k}^{(k)}(t) \cdot {}_{(k)}x_{s_k}(t) + \hat{Q}_{s_k}^{(k+1)}(t) \cdot {}_{(k+1)}x_{s_k}(t) \right] \cdot \frac{1}{x_{s_k}(t)} \\ &x_{s_k}(t) = {}_{(k)}x_{s_k}(t) + {}_{(k+1)}x_{s_k}(t), t \in {}_{(s_k)}\Delta_{i,j}^{(k-1)}, i \in \{1,2,\ldots,p_{k-1}\} \\ &\bigcup_{j=1}^{\sigma_k} {}_{(s_k)}\Delta_{i,j}^{(k-1)} \subseteq \zeta_i^{(k-1)} \end{aligned} \tag{2.13}$$

In this way, we obtain a *modified main programme of k-th grade* of c/b-CDLP type for each subinterval ${}_{(s_k)}\Delta_{i,j}^{(k-1)}$, $j=1,2,\ldots,\sigma_k$.

The minimum of the average solution is the one with the index s_k , while the vector with this index has already entered once or more times the basis during earlier iterations. In this case, the vector $\hat{P}_{s_j}^{(k)}(t)$ in the interval $\zeta_i^{(k-1)}$ fulfilling the conditions of optimality again enters the basis. We have to consider the possibility that the convex polyhedron $C_{s_k}(t)$ may not yet have been fully exploited; therefore, we again have to make allowance for the variation in it. Thus, we obtain a modified main programme of k-th grade for each subinterval ${}_{(s_k)}\Delta_{i,j}^{(k-1)}$ similar to programme (2.9) and we calculate it in the same way.

3 FUZZY LINEAR PROGRAMMING

3.1 Fuzzy sets, fuzzy numbers

Fuzzy sets differ from classical sets by rejecting the requirement that each object be either a member or a nonmember of any given set, Ruspini et al. [13], Ross [14]. A fuzzy set $\tilde{A}$ is a set of ordered pairs: $\tilde{A}=\{(x,\mu_{\tilde{A}}(x)) | x\in R\}$, where $\mu_{\tilde{A}}(x)$ is the membership function of *x*, which maps *R* to subset of the nonnegative real numbers whose supremum is finite. If $\sup_x \mu_{\tilde{A}}(x)=1$, the fuzzy set $\tilde{A}$ is called normal. Every function that maps $\tilde{A}$ universe of objects *X* onto $[0,1]$, is a fuzzy set, Ross [14]. A fuzzy set $\tilde{A}$ is convex if $\mu_{\tilde{A}}(tx+(1-t)y)\ge\min\{\mu_{\tilde{A}}(x),\mu_{\tilde{A}}(y)\}$, $x,y\in R,\ t\in[0,1]$.

Fuzzy number $\tilde{A}$ is a convex normalised fuzzy set $\tilde{A}$ on the real line R , such that a) exactly one $x_0\in R$ with $\mu_{\tilde{A}}(x_0)=1$ exists (x_0 is called the mean value of $\tilde{A}$) and b) $\mu_{\tilde{A}}(x)$ is piecewise continuous, Zimmermann [7]. The fuzzy number is in triangular form (Figure 1) with membership function:

$$\mu_{\tilde{A}}=\begin{cases}\dfrac{1}{b-a}x-\dfrac{a}{b-a} & \text{for } a\le x\le b\\ -\dfrac{1}{c-b}x+\dfrac{c}{c-b} & \text{for } b\le x\le c\\ 0 & \text{otherwise}\end{cases} \tag{3.1}$$

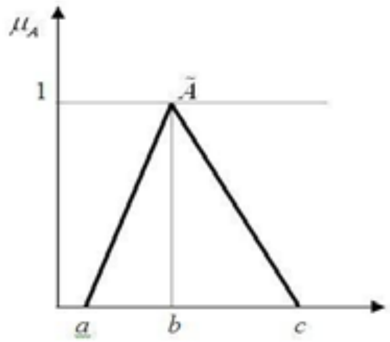

Figure 1: *Triangular fuzzy number* $\tilde{A}=(a,b,c)$

Definition (3.1) is very often modified in trapezoidal form (Figure 2). In this case, fuzzy number $\tilde{A}$ is a convex normalised fuzzy set $\tilde{A}$ on the real line R, such that a) it exists at least one $x_0 \in R$ with $\mu_{\tilde{A}}(x_0)=1$ and b) $\mu_{\tilde{A}}(x)$ is piecewise continuous.

$$\mu_{\tilde{A}}=\begin{cases} \frac{1}{\alpha}x-\frac{(a^L-\alpha)}{\alpha} & a^L-\alpha \le x \le a^L \\ 1 & a^L \le x \le a^U \\ -\frac{1}{\beta}x+\frac{a^U+\beta}{\beta} & a^U \le x \le a^U+\beta \\ 0 & otherwise \end{cases} \tag{3.2}$$

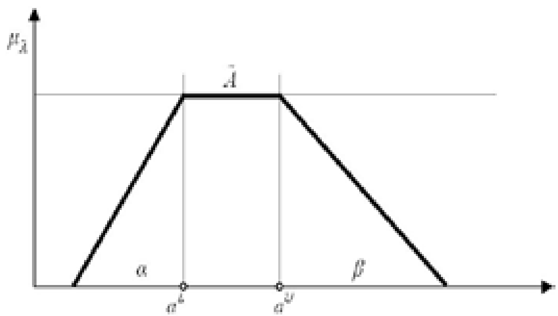

Figure 2: *Trapezoidal fuzzy number* $\tilde{A}=(a^L,a^U,\alpha,\beta)$

Let $F(R)$ be the set of trapezoidal fuzzy numbers, and $\tilde{a}=(a^L,a^U,\alpha_a,\beta_a)$, $\tilde{b}=(b^L,b^U,\alpha_b,\beta_b)$ two trapezoidal fuzzy numbers, $\lambda \in R$. Then:

$$\lambda\tilde{a}=(\lambda a^L,\lambda a^U,\lambda\alpha_a,\lambda\beta_a) \quad for\ \lambda>0$$

$$\lambda\tilde{a}=(\lambda a^U,\lambda a^L,-\lambda\beta_a,-\lambda\alpha_a) \quad for\ \lambda<0$$

$$\tilde{a}+\tilde{b}=(a^L+b^L,a^U+b^U,\alpha_a+\alpha_b,\beta_a+\beta_b)$$

$$\tilde{a}-\tilde{b}=\left(a^L-b^U,a^U-b^L,\alpha_a+\beta_b,\beta_a+\alpha_b\right)$$

Because of nature of simplex algorithms in linear programming problems, we need compare fuzzy numbers. One convenient method for doing so is the method of ranking functions. Ranking function $\mathbf{R}:F(R)\to R$ maps each fuzzy number into the real number. Let be $\tilde{a}$ and $\tilde{b}$ two trapezoidal fuzzy numbers. Then we define orders on $f(R)$, Nasseri and Ardil [8]:

$$\tilde{a}\underset{\mathbf{R}}{\geq}\tilde{b} \textit{ if and only if } \mathbf{R}(\tilde{a})\geq\mathbf{R}(\tilde{b})$$

$$\tilde{a}\underset{\mathbf{R}}{>}\tilde{b} \textit{ if and only if } \mathbf{R}(\tilde{a})>\mathbf{R}(\tilde{b})$$

$$\tilde{a}\underset{\mathbf{R}}{=}\tilde{b} \textit{ if and only if } \mathbf{R}(\tilde{a})=\mathbf{R}(\tilde{b})$$

There are many number-ranking functions, Chen [15]. For trapezoidal fuzzy number $\tilde{A}=\left(a^L,a^U,\alpha,\beta\right)$, one suggestion for the ranking functions is as follows:

$$\mathbf{R}(\tilde{A})=a^L+a^U+\frac{\beta-\alpha}{2} \tag{3.3}$$

3.2 Fuzzy linear programming

Fuzzy linear programming is an application of fuzzy set theory in linear decision-making problems; most of these problems are related to linear programming with fuzzy variables, Zimmermann [7].

In model (2.1), we shall assume that the decision maker can establish an aspiration level *z* for the value of the objective function he/she wants to achieve and that each of the constraints is modelled as a fuzzy set. Linear programming model (2.1) then becomes fuzzy linear programming, which is in canonical form (completed with slack and artificial variables), defined by expressions:

$$\begin{aligned} &opt\ \ \tilde{z}=(c,\tilde{x}) \\ \text{subject to}\ \ &A\tilde{x}=\tilde{b} \\ &\tilde{x}\geq 0 \end{aligned} \tag{3.4}$$

When we use the method of ranking fuzzy numbers, then the fuzzy linear programming (3.4) is written in the form:

$$\begin{aligned} &opt\ \ \tilde{z}\underset{R}{=}(c,\tilde{x}) \\ \text{s.t.}\ \ &A\tilde{x}\underset{R}{=}\tilde{b} \\ &\tilde{x}\underset{R}{\geq}0 \end{aligned} \tag{3.5}$$

$$c\in R^n,\tilde{x}\in\left[F(R)\right]^n,b\in\left[F(R)\right]^m,A\in R^{m\times n}$$

Fuzzy vector $\tilde{x}\in(F(R))^n$ is a feasible solution for the problem (3.5) if and only if $\tilde{x}$ satisfies the constraints the problem. A fuzzy feasible solution $\tilde{x}_{opt}$ is a fuzzy optimal solution for problem (3.5), if for all fuzzy feasible solutions $\tilde{x}$, we have $(c,\tilde{x}_{opt})\geq(c,\tilde{x})$ when the optimum means maximum or $(c,\tilde{x}_{opt})\leq(c,\tilde{x})$ when the optimum means minimum. In Nasseri and Ardil [8], the fuzzy simplex method for the minimum is given by the following algorithm. Suppose that we have a basic feasible solution with basis *B*. The procedure in Nasseri and Ardil [8] is done in the following steps:

Let the basic feasible fuzzy solution be given by $\tilde{x}_B \underset{\mathbf{R}}{=} B^{-1}\tilde{b}=\tilde{y}_0$. The fuzzy objective function is then $\tilde{z}\underset{\mathbf{R}}{=}c_B\tilde{x}_B=c_BB^{-1}\tilde{b}\underset{\mathbf{R}}{=}c_B\tilde{y}_0$.

In the next step, we calculate a) $w=c_BB^{-1}$ and b) rank of fuzzy number $\tilde{y}_0$: $\mathbf{R}(\tilde{y}_0)=y_0$. For each nonbasic variable, we then calculate simplex multiplier π_j as usual: $\pi_j=z_y-c_j=c_BB^{-1}a_j-c_j$, $j\in\{1,2,\ldots,n\}$.

If simplex multiplier $\pi_s=\max_j\{\pi_j\}\leq 0$, then the current solution is optimal. If $\pi_s=\min_j\{\pi_j\}>0$, then we have to proceed to the simplex algorithm.

Calculate $y_s=B^{-1}a_{is}$. When $y_s\leq 0$, the optimal solution does not exist. If $y_s>0$, then determine the index of the variable $\tilde{x}_r$ leaving the basis as follows: $\frac{y_{r0}}{y_{rs}}=\min_i\left\{\frac{y_{i0}}{y_{is}},y_{is}>0\right\}$. Next, update $\tilde{y}_{i0}$ by replacing with $\tilde{y}_{i0}-\frac{\tilde{y}_{r0}}{y_{rs}}\cdot y_{is}$ for $i\neq r$ and y_{r0} by replacing with $\frac{\tilde{y}_{r0}}{y_{rs}}$. Then update object function $\tilde{z}$ by replacing $\tilde{z}-\frac{\tilde{y}_{r0}}{y_{rs}}(z_s-c_s)$ and update matrix *B* by replacing its elements a_{ir} with a_{is} and proceed to step 2.

4 FUZZY DYNAMIC LINEAR PROGRAMMING

4.1 Fuzzy function

A fuzzy function may be explained by extending the definition of a classical function, TU Dresden, [19]. A classical function is a single-valued mapping of the elements t from the fundamental set $t\subseteq R$ onto the elements x of the fundamental set $x(t)\subseteq R$. The fuzzy function $\tilde{x}(t)\subseteq R$ may thus also be interpreted as being a set of fuzzy results or fuzzy functional values $\tilde{x}_t\in F(X)$ belonging to specified $t\in F(T)$: $\tilde{x}(t)=\{\tilde{x}_t=\tilde{x}(t)\ \forall t \mid t\in F(T)\}$. In structural analysis, the fundamental set T may contain crisp parameters, such as the time coordinate.

If the fundamental set $F(T)$ represents the time coordinate, the fuzzy function is referred to as a *fuzzy process* (Fig. 3).

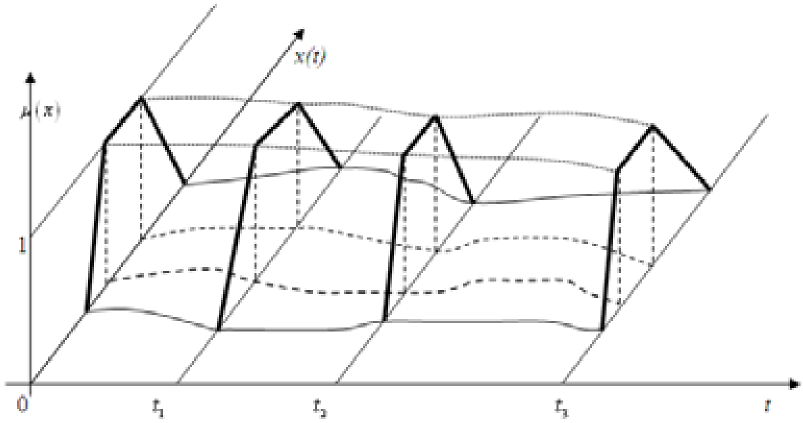

Figure 3: *Fuzzy process*

4.2 Fuzzy dynamic linear programming

Fuzzy dynamic linear programming (FDLP) is the synthesis of the problems (2.2) or (2.3) and (3.4).

$$\begin{aligned} & opt\ \tilde{z}(t) \underset{R}{=} (\tilde{c}(t), \tilde{x}(t)) \\ & \quad \tilde{A}(t)\tilde{x}(t) \cong \tilde{b}(t) \\ & \quad \tilde{x}(t) \tilde{\geq} 0 \end{aligned} \tag{4.1}$$

$$\tilde{c}(t) \in R^n, \tilde{x}(t) \in [F(R)]^n$$
$$\tilde{b}(t) \in [F(R)]^m, \tilde{A}(t) \in R^{m \times n}$$

This problem has an optimal solution under specific conditions, while the simplex algorithm depends on time interval and on the type of fuzzy dynamic functions.

To set up the algorithm and prove the existence of the solution as well as the optimum method of calculating this problem, a step-by-step approach is used and the following three subproblems ($t \in [0, T], T < \infty$) are calculated:

a) if $\tilde{A}(t) = \tilde{A}(0), \tilde{c}(t) = \tilde{c}(0)$, the subproblem called b-FDLP occurs;

b) if $\tilde{A}(t) = \tilde{A}(0), \tilde{b}(t) = \tilde{b}(0)$, the subproblem called c-FDLP occurs;

c) if $\tilde{A}(t) = \tilde{A}(0)$, the subproblem called c/b-FDLP occurs.

In this article, b-FDLP is studied:

$$\begin{aligned} &opt\ \ \tilde{z}(t)=(\tilde{c},\tilde{x}(t)) \\ &A\tilde{x}(t)\cong\tilde{b}(t) \\ &\tilde{x}(t)\gtrsim 0 \end{aligned} \tag{4.2}$$

If we sign the union of areas of admissibility of k-th solution with D_k, and the union of areas of structurally of the base of k-th solution with S_k, we can prove:

Theorem 6: *If the following conditions are fulfilled:*

1. $\tilde{b}^{(0)}(t)\in R_b$, $t\in D_k\bigcap S_k\subseteq[0,T]$,

2. $a^{(p-1)}_{i,s^{(p-1)}_{p-1}}>0$ *for at least one* $i\in\{1,2,\ldots,m\}$, $p=1,2,\ldots,k$,

3. $\bar{c}^{(p-1)}_j<0$ *for at least one nonbasic* $j=s^{(p-1)}_{p-1}$ *and* $p=1,2,\ldots,k$,

then for problem (4.2) in the non-empty area $D_k\bigcap S_k$, *one segmentally stationary feasible basic solution* $\tilde{x}^{(k)}(t)\in R_b$ *exists.*

Theorem 7: *If the following conditions are fulfilled:*

1. $\tilde{b}^{(0)}(t)\in R_b$, $t\in D_{k_0}\bigcap S_{k_0}\subseteq[0,T]$,

2. $a^{(p-1)}_{i,s^{(p-1)}_{p-1}}>0$ *for at least one* $i\in\{1,2,\ldots,m\}$, $p=1,2,\ldots,k_0$,

3. $\bar{c}^{(p-1)}_j<0$ *for at least one nonbasic* $j=s^{(p-1)}_{p-1}$ *and* $p=1,2,\ldots,(k_0-1)$,

4. $\bar{c}^{(k)}_j\geq 0$ *for every* $j\in\{1,2,\ldots,n\}$,

5. $k_0\in R$ *for every* $t\in D_{k_0}\bigcap S_{k_0}$,

then for problem (4.2) in the non-empty area $D_{k_0}\bigcap S_{k_0}$, *one segmentally structurally stationary optimal feasible basic solution* $\tilde{x}^{(k_0)}(t)\in R_b$ *exists.*

Following the simplex algorithm, the optimal solution $\tilde{x}^{(k_0)}(t)$ is

$$\begin{aligned} &\tilde{x}^{(k_0)}(t)=\left[B^{(k_0)}_{\{\tau_{k_0}\}}\right]^{-1}\cdot\tilde{b}^{(0)}(t) \\ &t\in\Delta^{(k_0)}_{\tau_{k_0}},\tau_{k_0}=1,2,\ldots,p_{k_0}\left(\tau_1,\tau_2,\ldots,\tau_{k_0-1}\right) \end{aligned} \tag{4.3}$$

Under the conditions of Theorems 6 and 7, we can always obtain the optimum structurally stationary basic solution $\tilde{x}^{k_0(t)}$ of the problem (4.2).

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5 NUMERICAL EXAMPLE

5.1 Crisp linear programming

$$\begin{aligned} \min \quad & z = 60x_1 + 100x_2 \\ s.t. \quad & 6x_1 + 2x_2 \geq 28 \\ & 3x_1 + 6x_2 \geq 24 \\ & x_1 \geq 0, x_2 \geq 0 \end{aligned}$$

By adding slack and artificial variables, we may rewrite

$$\begin{aligned} \min \quad & z = 60x_1 + 100x_2 + 0 \cdot x_3 + 0 \cdot x_4 + 200x_5 + 200x_6 \\ s.t. \quad & 6x_1 + 2x_2 - x_3 \quad + x_5 \quad \geq 28 \\ & 3x_1 + 6x_2 \quad - x_4 \quad + x_6 \geq 24 \\ & x_1, x_2, x_3, x_4, x_5, x_6 \geq 0 \end{aligned}$$

***Table 1**: Simplex tableau for crisp LP*

z	x_1	x_2	x_3	x_4	x_5	x_6	b
1	1740	1500	-200	-200	0	0	10400
0	6	2	-1	0	1	0	28
0	3	6	0	-1	0	1	24
1	0	920	90	-200	-290	0	2280
0	6	2	-1	0	1	0	28
0	0	5	½	-1	- ½	1	10
1	0	0	-2	-16	-198	-184	440
0	6	0	$-6/5$	$2/5$	$6/5$	$-2/5$	24
0	0	5	½	-1	-½	1	10

Optimal solution: $x_1 = 4, x_2 = 2, z_{\min} = 440$

5.2 Fuzzy linear programming

$$\begin{aligned} \min \quad & \tilde{z} \underset{R}{=} 60\tilde{x}_1 + 100\tilde{x}_2 \\ s.t. \quad & 6\tilde{x}_1 + 2\tilde{x}_2 \underset{R}{\geq} (26,30,1,2) \\ & 3\tilde{x}_1 + 6\tilde{x}_2 \underset{R}{\geq} (23,26,3,1) \\ & \tilde{x}_1, \tilde{x}_2 \underset{R}{\geq} 0 \end{aligned}$$

By adding slack and artificial variables we have

$$\begin{aligned} \min \quad & \tilde{z} \underset{R}{=} 60\tilde{x}_1 + 100\tilde{x}_2 + 0\cdot\tilde{x}_3 + 0\cdot\tilde{x}_4 + 200\tilde{x}_5 + 200\tilde{x}_6 \\ s.t. \quad & 6\tilde{x}_1 + 2\tilde{x}_2 - \tilde{x}_3 \quad + \tilde{x}_5 \underset{R}{\geq} (26,30,5,1) \\ & 3\tilde{x}_1 + 6\tilde{x}_2 \quad - \tilde{x}_4 \quad + \tilde{x}_6 \underset{R}{\geq} (23,26,3,1) \\ & \tilde{x}_1, \tilde{x}_2, \tilde{x}_3, \tilde{x}_4, \tilde{x}_5, \tilde{x}_6 \underset{R}{\geq} 0 \end{aligned}$$

***Table 2**: Simplex tableau for fuzzy LP*

$\tilde{z}$	$\tilde{x}_1$	$\tilde{x}_2$	$\tilde{x}_3$	$\tilde{x}_4$	$\tilde{x}_5$	$\tilde{x}_6$	$\tilde{b}$	Rank
1	1740	1500	-200	-200	0	0	(9800,11200,1600,400)	20400
0	6	2	-1	0	1	0	(26,30,5,1)	54
0	3	6	0	-1	0	1	(23,26,3¸1)	48
1	0	920	90	-200	-290	0	(2260,2500,150,110)	4740
0	6	2	-1	0	1	0	(26,30,5,1)	54
0	0	5	½	-1	- ½	1	(10,11,1/2,1/2)	21
1	0	0	-2	-16	-198	-184	(420,476,58,18)	876
0	6	0	$-6/5$	$2/5$	$6/5$	$-2/5$	(22,128/5,24/5,4/5)	228/5
0	0	5	½	-1	-½	1	(10,11,1/2,1/2)	21

Optimal solution: $\tilde{x}_1 = \left(\frac{11}{3}, \frac{64}{15}, \frac{4}{5}, \frac{2}{15}\right), \tilde{x}_2 = \left(2, \frac{11}{5}, \frac{1}{10}, \frac{1}{10}\right), \tilde{z}_{\min} = (420,476,58,18)$

$$\tilde{z}_{\min} = 60\tilde{x}_1 + 100\tilde{x}_2 = 60\cdot\left(\frac{11}{3}, \frac{64}{15}, \frac{4}{5}, \frac{2}{15}\right) + 100\cdot\left(2, \frac{11}{5}, \frac{1}{10}, \frac{1}{10}\right) = (420,476,58,18)$$

5.3 Dynamic linear programming

$$\begin{aligned} \min \quad & z = 60x_1 + 100x_2 \\ s.t. \quad & 6x_1 + 2x_2 \geq 28 - t \\ & 3x_1 + 6x_2 \geq 24 + t \\ & x_1 \geq 0, x_2 \geq 0 \\ & t \in [0,5] \end{aligned}$$

By adding slack and artificial variables, we may rewrite

$$\begin{aligned} \min \quad & z = 60x_1 + 100x_2 + 0\cdot x_3 + 0\cdot x_4 + 200x_5 + 200x_6 \\ s.t. \quad & 6x_1 + 2x_2 - x_3 \quad + x_5 \quad \geq 28 - t \\ & 3x_1 + 6x_2 \quad - x_4 \quad + x_6 \geq 24 + t \\ & x_1, x_2, x_3, x_4, x_5, x_6 \geq 0, t \in [0,5] \end{aligned}$$

***Table 3**: Simplex tableau for dynamic LP*

z	x_1	x_2	x_3	x_4	x_5	x_6	b
1	1740	1500	-200	-200	0	0	10400
0	6	2	-1	0	1	0	28-t
0	3	6	0	-1	0	1	24+t
1	0	920	90	-200	-290	0	2280+290t
0	6	2	-1	0	1	0	28-t
0	0	5	½	-1	- ½	1	$10+\frac{3}{2}t$
1	0	0	-2	-16	-198	-184	440+14t
0	6	0	$-6/5$	$2/5$	$6/5$	$-2/5$	$24-\frac{8}{5}t$
0	0	5	½	-1	-½	1	$10+\frac{3}{2}t$

Optimal solution: $x_1 = 4 - \dfrac{4}{15}t,\ x_2 = 2 + \dfrac{3}{10}t,\ z_{\min} = 440 + 14t$

The optimal solution is valid over the whole time interval $[0,5]$, because $x_1 \geq 0$ for $0 \leq t \leq 15$ and $x_2 \geq 0$ for every $t \geq 0$.

5.4 Fuzzy dynamic linear programming

$$
\begin{aligned}
\min\quad & z = 60\tilde{x}_1 + 100\tilde{x}_2 \\
s.t.\quad & 6\tilde{x}_1 + \tilde{2}x_2 \geq 28 - t \\
& 3\tilde{x}_1 + 6\tilde{x}_2 \underset{R}{\geq} (23,26,3,1) \\
& \tilde{x}_1 \underset{R}{\geq} 0, \tilde{x}_2 \underset{R}{\geq} 0 \\
& t \in [0,5]
\end{aligned}
$$

By adding slack and artificial variables, we may rewrite

$$
\begin{aligned}
\min\quad & \tilde{z} \underset{R}{=} 60\tilde{x}_1 + 100\tilde{x}_2 + 0\cdot\tilde{x}_3 + 0\cdot\tilde{x}_4 + 200\tilde{x}_5 + 200\tilde{x}_6 \\
s.t.\quad & 6\tilde{x}_1 + 2\tilde{x}_2 - \tilde{x}_3 \quad + \tilde{x}_5 \quad \geq (26-t, 30-t, 2, 2) \\
& 3\tilde{x}_1 + 6\tilde{x}_2 \quad - \tilde{x}_4 \quad + \tilde{x}_6 \underset{R}{\geq} (23,26,3,1) \\
& \tilde{x}_1, \tilde{x}_2, \tilde{x}_3, \tilde{x}_4, \tilde{x}_5, \tilde{x}_6 \underset{R}{\geq} 0, t \in [0,5]
\end{aligned}
$$

***Table 4**: Simplex tableau for fuzzy dynamic LP*

$\tilde{z}$	$\tilde{x}_1$	$\tilde{x}_2$	$\tilde{x}_3$	$\tilde{x}_4$	$\tilde{x}_5$	$\tilde{x}_6$	$\tilde{b}$	Rank
1	1740	1500	-200	-200	0	0	(9800-200t,11200-200t,1000,600)	20800-400t
0	6	2	-1	0	1	0	(26-t,30-t,2,2)	56-2t
0	3	6	0	-1	0	1	(23,26,3,1)	48
1	0	920	90	-200	-290	0	(2260+90t,2500+90t,420,	4560+

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							20)	180t
0	6	2	-1	0	1	0	(26-t,30-t,2,2)	56-2t
0	0	5	½	-1	- ½	1	(10+0,5t,11+0,5t,2,0)	20+t
1	0	0	-2	-16	-198	-184	(420-2t,476-2t,52,20)	880-4t
0	6	0	$-\frac{6}{5}$	$\frac{2}{5}$	$\frac{6}{5}$	$-\frac{2}{5}$	$\left(22-\frac{6}{5}t,\frac{128}{5}-\frac{6}{5}t,\frac{6}{5},2\right)$	$48-\frac{12}{5}t$
0	0	5	½	-1	-½	1	$\left(10+\frac{1}{2}t,11+\frac{1}{2}t,2,0\right)$	20+t

Optimal solution:

$$\tilde{x}_1(t)=\left(\tfrac{22}{6}-\tfrac{1}{5}t,\tfrac{128}{30}-\tfrac{1}{5}t,\tfrac{1}{5},\tfrac{1}{3}\right),\tilde{x}_2(t)=\left(2+\tfrac{1}{10}t,\tfrac{11}{5}+\tfrac{1}{10}t,\tfrac{2}{5},0\right),z_{\min}=\left(420-2t,476-2t,52,20\right)$$

$$z_{\min}=60x_1+100x_2=60\left(\tfrac{22}{6}-\tfrac{1}{5}t,\tfrac{128}{30}-\tfrac{1}{5}t,\tfrac{1}{5},\tfrac{1}{3}\right)+100\left(2+\tfrac{1}{10}t,\tfrac{11}{5}+\tfrac{1}{10}t,\tfrac{2}{5},0\right)=\left(420-2t,476-2t,52,20\right)$$

6 CONCLUSION

The FDLP algorithm can be applied in very concrete real situations, Usenik, [2], [16], [17], [18].

Interval $[0,T]$ over which time functions $\tilde{b}_i(t)\in R_b$, $i=1,2,\ldots,m$ have been defined and in which we have been calculating FDLP continually, as a rule breaks up into subintervals in the process of working out the problem. The union of these intervals is smaller or at least the same as the initial interval $[0,T]$. It may therefore occur that in some cases, which depend on the form of time functions, the initial finite interval $[0,T]$ breaks up into quite a large number of non-empty subintervals. In such cases, substantial difficulties arise in solving concrete problems, because theoretically optimal solutions in very short time intervals generally cannot give optimum results in practical applications. This is the reason research is directed towards defining additional limiting conditions that will help alleviate this problem. Because of the possibility in the applications in solving concrete problems in the field of optimisation, further research will emphasise the introduction of the results of FDLP in this sphere. It is obvious that some new approaches and new conditions will have to be introduced. One of very interesting and successful possibilities is an inclusion of a neural network in the algorithm of fuzzy dynamic linear programming problems.

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SYSTEMATIC APPROACH TO NUCLEAR MAINTENANCE TRAINING

SISTEMATIČNI PRISTOP K USPOSABLJANJU VZDRŽEVALNEGA OSEBJA V JEDRSKI ENERGETIKI

Marko Živič[ℜ]

Keywords: systematic approach to training, performance-based training, nuclear maintenance, qualification, simulator loop

Abstract

Qualified personnel directly influence safe and reliable nuclear power plant operations. Operations, surveillance and maintenance personnel are directly responsible for plant safety as well as reliable power generation with their correct professional actions. The training and qualification process in the nuclear power generation industry is separated from the power generation processes. The training and qualification process needs to be supported with proper methodology and suitable training facilities able to ensure transparent and efficient knowledge and skills transfer. The Systematic Approach to Training (SAT) methodology is used as a systematic process that covers the entire training circle from the identification of training needs to training design, training development and training implementation. The final steps of the SAT process are the qualification of training attendees and the documentation of the performed training and qualification process. Performance-based training is performed either on plant equipment mock-ups or on simulator loops whose operation and control is similar to real operating power and safety systems.

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Povzetek

Varno in zanesljivo obratovanje jedrske elektrarne je neposredno povezano s preverjeno usposobljenim osebjem, ki je zadolženo za upravljanje, nadzor in vzdrževanje tekočih procesov pretvorb energij in procesov kratkoročnega ter dolgoročnega zagotavljanja varnega ter stabilnega delovanja jedrske elektrarne. Zagotavljanje usposobljenega osebja v jedrski energetiki predstavlja ločen proces, ki mora biti podprt z ustrezno metodologijo in primernimi učnimi pomagali za učinkovit in pregleden prenos znanja ter spretnosti. Metodologija sistematičnega pristopa k usposabljanju (SAT) je podlaga za določitev učnih potreb, razvoja in izvedbe opravilno usmerjenih usposabljanj, preverjanja usposobljenosti ter ustreznega dokumentiranja izvedenega procesa. Proces opravilno usmerjenega usposabljanja mora potekati na ustreznih učnih pomagalih, ki se nanašajo bodisi na posamezne tehnološke komponente bodisi na simuliranje celovitejših procesov, ki potekajo v procesih pretvorbe energije. V ta namen se uporabljajo modeli opreme in sistemov, ki imajo podobne krmilnotehnološke značilnosti kot dejansko vgrajena oprema in varnostni sistemi v energetskem delu elektrarne.

1 INTRODUCTION

The energy transformation process from nuclear reaction to electricity is the main purpose of a nuclear power plant. To transform nuclear energy to electricity by using nuclear reactions, nuclear safety principles had to be developed. The basic principle of nuclear safety is to prevent the release of radioactive materials during normal and incidental operation. The interruption of the chain reaction in a nuclear reactor and the removal of the residual heat from the reactor, which is produced by residual decay of fission products and the thermal inertia of reactor fuel are key activities to assure safety control of the process.

The key points of the energy transformation process are to control the nuclear chain reaction and to assure the stable operation of the power plant, which means that the energy transformation process is continuously in progress. These goals can be achieved with high-quality design, construction, testing, operation and maintenance of a power plant. Operation and maintenance activities are directly performed by qualified craft personnel. There is a subsequent need to assure a specific number of qualified personnel able to perform surveillance, operation and maintenance activities on-site. The recruitment process should be based on required education and additional verification of the specific abilities of personnel; finally, the personnel should pass specific training and qualification processes to be able to perform specific plant activities. The dynamics and difficulties of the work require the successive introduction of new personnel to plant activities. Firstly, it is recommended that new personnel to gain specific experience in helping regular operation and maintenance activities; secondly, they must pass training and qualification programs that cover specific working areas. This process assures continuous knowledge and skills transfer, and provides a sufficient number of technically competent and proficient workers.

The Systematic Approach to Training (SAT) methodology is well-known in the nuclear power industry [1], [2]. Furthermore, in many countries, SAT-based training is the accepted standard for training of NPP personnel [3], [4]. This methodology provides a standard framework for training development on a required competence basis. In other words, it can be said that required working competences are transformed to training goals, and SAT supports the whole

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process from training preparation through implementation to training evaluation. This process assures efficient and controlled process of training.

2 WORK CONTROL AND QUALIFIED PLANT PERSONNEL

For its safe and reliable operation, a nuclear power plant requires precisely defined work control and the performance of activities in accordance with established standards. Working activities are done efficiently and transparently, and special attention is paid to traceability. Work control process supports (coordinates, manages, controls) the activities of operation, maintenance, modification, surveillance, safety evaluation, etc. Work control is especially focused on maintenance activities, scheduling, planning and implementation. There are two key support elements for efficient and reliable work control implementation:

- Efficient administrative support, and
- Well trained and qualified personnel.

Figure 1 shows standard operation and support in family plants by INPO, [6].

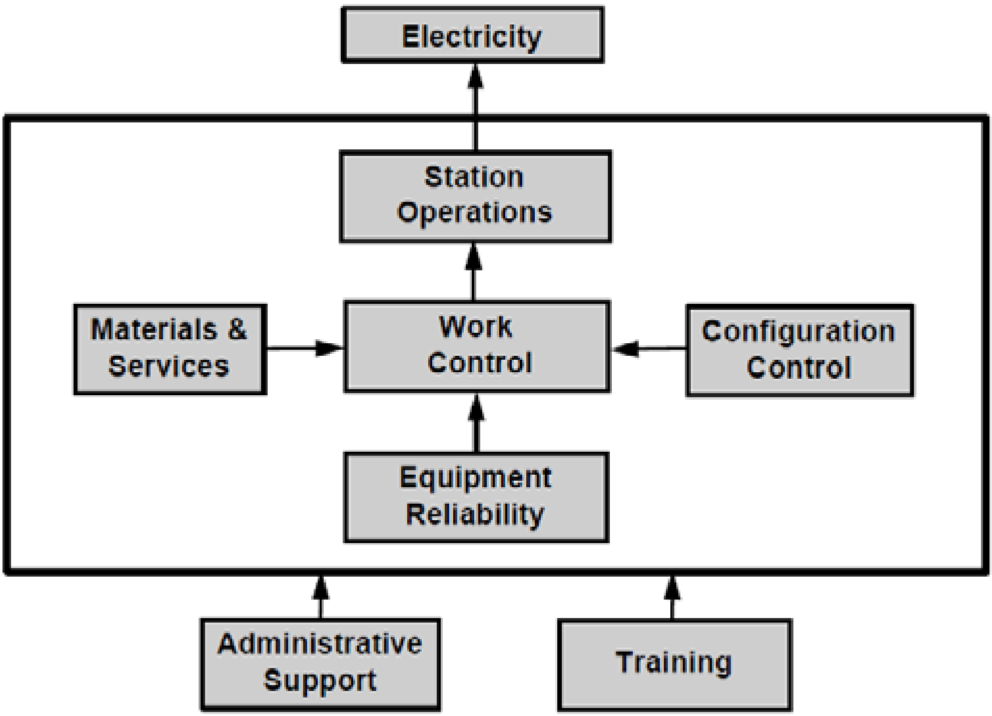

Figure 1: *Operation and support of standard nuclear plants*

3 TRAINING SYSTEM DEVELOPMENT

Training system development process at the specific plant is focused on at least the following items:

- The personnel involved in training should be professional. Performers of training should be qualified, in both their area of expertise and in training, and willing to present their knowledge and skills to nonqualified personnel. The nonqualified personnel should be able to receive specific knowledge and skills as well as respect the training and qualification process.
- Training and qualification process should be supported by proper methodology. A methodology should be able to support the training and qualification process in all phases, i.e. identifying training needs, designing, developing, and implementing training and finally, evaluating and documenting the whole process.
- Training facilities such as classrooms and laboratories, training aids, simulators, simulator loops and equipment mock-ups are important elements in training development and performance.
- The complexity of the training process requires efficient administrative support. Providing accurate and complete documentation for tracking and recording the results of qualification for each individual is an important and necessary feature. The administrative support should be able to identify the qualifications necessary for specific job positions, the individuals assigned, and the tasks or duties each individual is qualified to perform. Additionally, the documentation should facilitate management scheduling and the assignment of personnel to perform work.

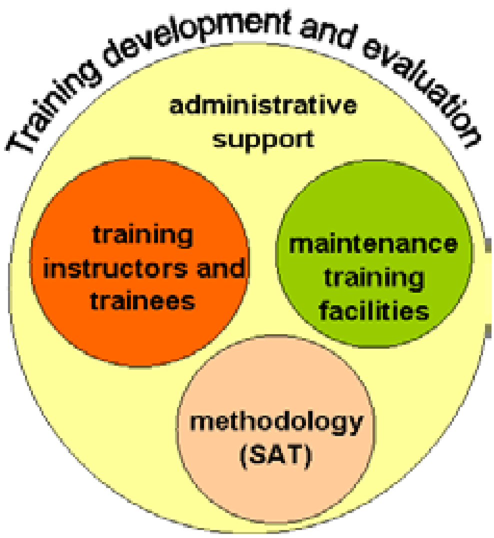

Figure 2: *Nuclear maintenance training system*

3.1. Personnel at training process (Maintenance Instructors and Training Attendees)

Nuclear maintenance training is implemented to achieve, maintain, and improve maintenance personnel knowledge, skills, and performance in order to support plant safety and plant performance goals. Nuclear maintenance consists of a wide range of safety- and reliability-related activities that are performed by numerous specialists and their assistants. Specific

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technical areas and suggested maintenance training topics are described in documents [7], [8]. The training is an important additional tool to assure activities are done in a safe, reliable and timely manner.

The quality of the entire training process depends on efficient knowledge and skills transfer. Careful selection and designation of competent trainers and evaluators is one of the key elements to assure professionalism at the training process. Mostly, trainers are not professional trainers but specialists in specific maintenance areas and they are designated among the most knowledgeable and experienced individuals at the plant, i.e. subject matter experts. Their knowledge and skills in maintenance and the ability to accomplish specific tasks for which they could be trainers or evaluators should be satisfactorily recognised and evaluated.

The training attendees or candidates should possess satisfactory prerequisite knowledge to be able to receive training. Administrative controls are established to verify that trainees meet the prescribed fundamental, technical, and administrative prerequisites. New maintenance personnel should receive fundamental training and then complete the portions of training needed to attain the appropriate qualification level.

Figure 3 shows upgrade of fundamental, technical, and administrative prerequisites, [8].

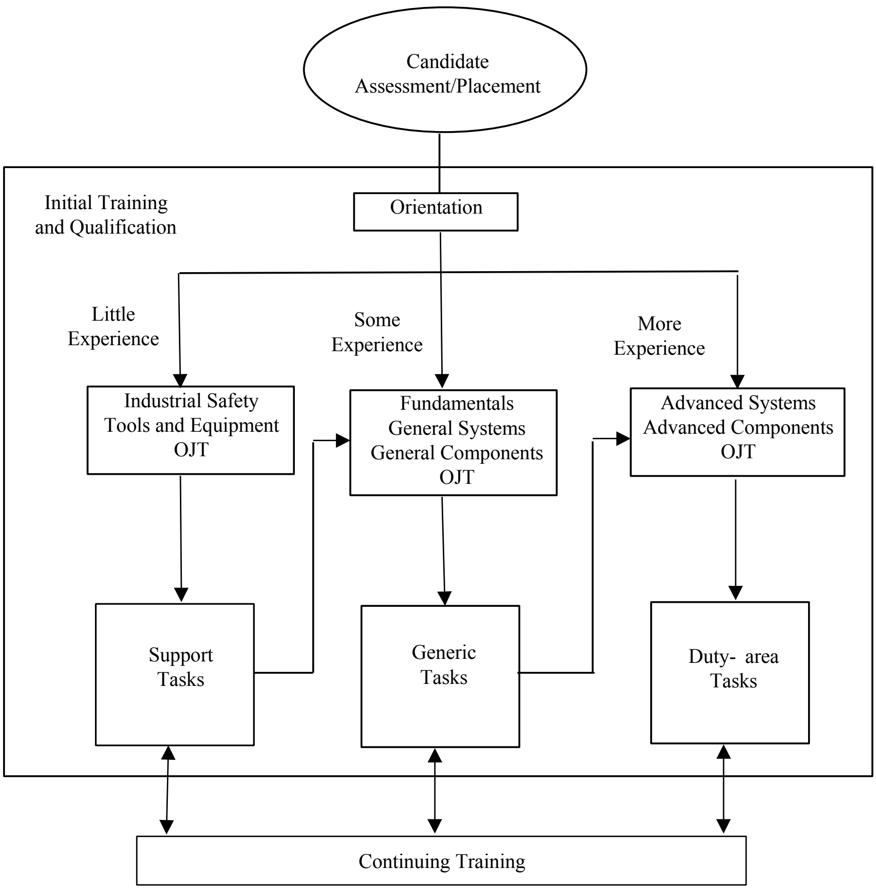

Figure 3: *Typical Training Sequence*

3.2. Methodology – Systematic Approach to Training

The complexity of maintenance activities at nuclear power plants requires the highest level of maintenance personnel competence. The required levels of maintenance staff performance can be achieved when the training develops the skills and knowledge needed for safe, effective job performance. The training and qualification processes of maintenance craft personnel are based on the SAT methodology.

The success of the systematic approach in meeting complex training requirements has been demonstrated with its extensive use in the aerospace, health, and defence industries. It has gained acceptance in each of these fields by improved training effectiveness, accountability, and control. It offers similar benefits to the commercial nuclear power industry. Since November 1993, the SAT methodology has been required by Nuclear Regulatory Commission for nuclear operators in the USA, [9]. Furthermore, the methodology has been recommended by the IAEA for training nuclear power plant personnel [10]. Consequently, the SAT methodology has become a general approach to develop training system in specific areas of nuclear power industry.

There are many guidelines for establishing a training system on the basis of SAT. The guidelines from INPO, IAEA, and WANO are focused on the nuclear power industry [5], [10], [12].

Cited next are some fundamentals from the SAT guidelines to remember the process goals and basic steps or phases of a process:

An effective, performance-based training and qualification system includes activities to accomplish the following:

- Identify what training should be provided for each position (based on analysis of job performance requirements and initial qualifications of trainees) [11],
- Design and develop training programs with explicit learning objectives and appropriate content,
- Conduct training as designed,
- Ensure that trainees master learning objectives before they begin working in their assigned positions,
- Evaluate training effectiveness and use these results to maintain and improve training.

Training must be designed to accommodate the expected input, and it must be evaluated on the quality of output. The training system should be adjusted to meet the needs of the personnel selected to participate, and be modified, as necessary, to produce certain duty area performance levels required for safe and reliable plant operation.

3.2.1. Training System Development Process

SAT is a methodology for developing performance-based training for meeting nuclear plant job requirements. The training system development process includes five phases: analysis, design, development, implementation, and evaluation. The overall system relies on feedback for

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monitoring performance and adapting to changing conditions and requirements. Each phase within the system uses feedback to identify and correct problems. SAT supports a logical progression from the identification of the competences to the development and implementation of training towards achieving these competences. As SAT is a general training approach for the nuclear industry, it is implemented in nuclear maintenance as well.

Figure 4 shows five phases of training system development. It is important that evaluation of each phase continuously improves the whole training process as well as staff performance.

In Figure 5, key activities are shown in each of five phases of SAT, [14].

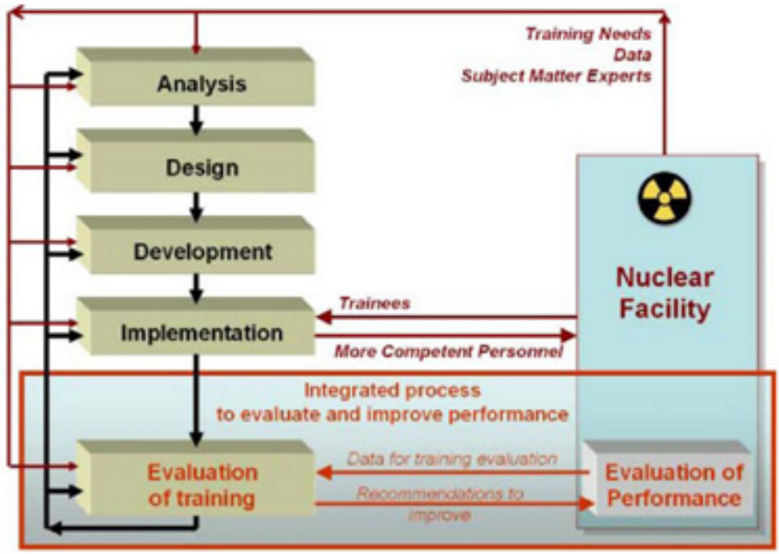

Figure 4: *Systematic approach to training process [13]*

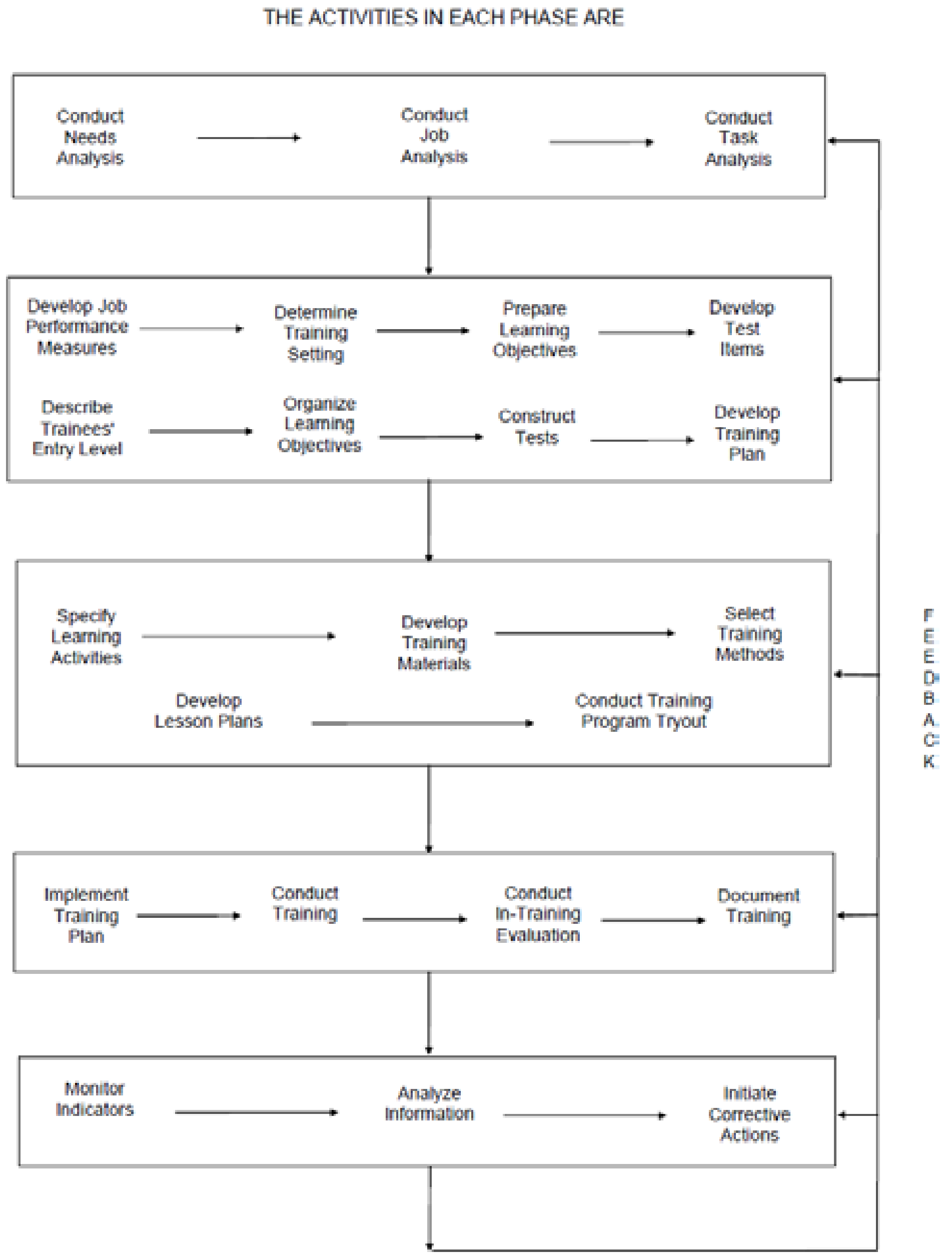

Figure 5: *Main activities in single phases (analysis, design, development, implementation, evaluation) of SAT*

3.2.2. OJT – On the Job Training

On the Job Training (OJT) is a performance-based training method, based on the SAT methodology. To perform maintenance, surveillance or operations activities important for the safe and stable operation of a power plant, it is essential to assure that the activities are carried out correctly. When the reliability of task performance has a crucial impact on plant operation and maintenance, it needs to be verified that tasks are performed by qualified personnel. OJT covers the training and qualification process and clearly helps in the phase of obtaining qualifications. The purpose of OJT training and evaluation is to teach and evaluate job-related knowledge and skills within the job environment. OJT provides hands-on experience for the trainee. Evaluation of the conducting of a task is used as a part of the qualification process, in which a final knowledge and proficiency check is used to determine the trainee's qualification for tasks or duty areas.

The main steps of OJT and task performance evaluation include the following, [15]:

- instruct trainees, including supervised practice, on key skills and knowledge required for job or task performance,
- evaluate trainee's achievement of key skills and knowledge required for satisfactory job or task performance, using performance, simulation, and discussion,
- assist management in determining that workers are qualified to perform the assigned jobs or tasks in a safe, efficient, and effective manner.

Both OJT and task performance evaluation are integral parts of the hands-on training phases of training programs in the nuclear industry. Individual skills are typically developed during OJT. The independent demonstration of knowledge and skills in task performance evaluation is an important part of determining whether plant personnel are qualified to perform tasks safely and reliably. OJT and task performance evaluation are most effective when conducted as closely as possible to the conditions that will be experienced at the plant.

3.3. Training Facilities – simulator loops, equipment mock-ups

It is impractical to conduct all OJT and task performance evaluation on actual plant equipment. In these cases, it is necessary to simulate equipment and work control conditions. Nuclear power plants approach this issue individually. Many of them have developed specific simulator loops. Additional support to maintenance training and qualification process is provided by mock-ups produced from discarded equipment from the plant. Facilities such as loop simulators, and mock ups reflect the actual plant equipment and working environment, so the training is performed closely to real work control conditions. Thus, the training can be performed independently from plant conditions. Moreover, there is no impact on the operation of plant systems and the training can be repeated until the qualification criteria are reached.

Figure 6 shows a flow diagram of the simulator loop at Krško NPP. The flow loop’s detailed description and purpose are described in [16].

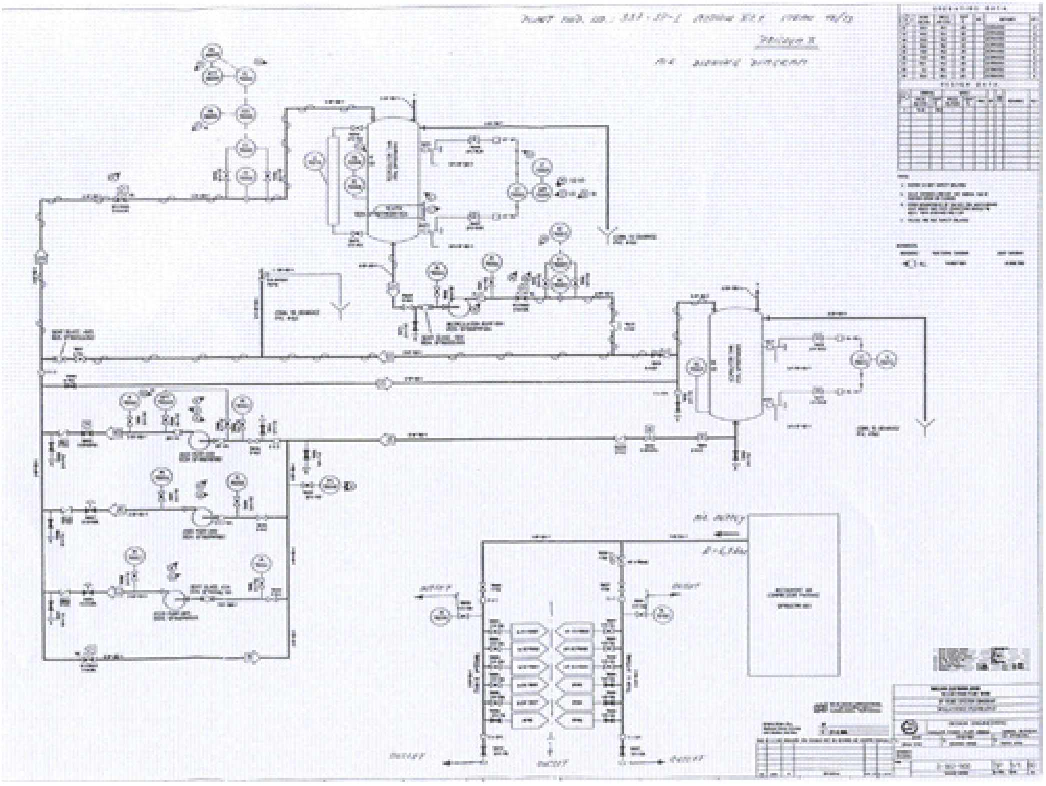

Figure 6: *Krško NPP simulator loop flow diagram*

Figure 7 shows training on centrifugal pump mock-ups with different shaft sealing at Krško NPP.

Figure 8 shows some of the training mock-ups at South Texas Project Nuclear Station.

Figure 7: *Training on pump mock-ups*

Figure 8: *Training mock-ups at STP*

3.4. Administration and Information support

Effective administrative systems, including accurate databases, are used to administer and manage training activities. Dealing with the training requirements, preparing annual training

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plans, providing accurate and complete documentation for tracking and recording the results of qualification for each individual is an important and necessary management tool that needs effective IT support. The IT software is mostly part of the plant's information system. Therefore, the administrative issue of the training is mentioned as a support activity of the process.

4 CONCLUSION

Nuclear power plant design is in compliance with the demanding design requirements regarding safe plant operation. It takes into account not only verified and confirmed technological solutions, but also requires the development and maintenance of a high safety culture of personnel who have either a direct or indirect impact on the control of energy process.

The SAT methodology ensures the on-going provision of competent maintenance personnel in a nuclear facility. The effectiveness of SAT is recognised in a consistent, traceable and transparent process ranging from the identification of training needs to the final goal of ensuring qualified staff for specific maintenance tasks. The SAT methodology ensures the efficient transfer of knowledge and skills to less experienced employees.

In addition to pursuing good staffing policy, suitable training facilities and proper administrative as well as information technology, support must be ensured for effective training.

This article summarises the written instructions and recommendations for establishing training in a nuclear facility. On the basis of hands-on experience at the Krško NPP, it highlights key elements of maintenance personnel training.

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