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Knowledge Based Inspection:
Modelling Complex Processes with the
integrated Safeguards Modelling Method (iSMM)

Verfasser

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Abstract

Increased level of complexity in almost every discipline and operation today raises the demand for knowledge in order to successfully run an organization whether to generate profit or to attain a non-profit mission. Traditional way of transferring knowledge to information systems rich in data structures and complex algorithms continue to hinder the ability to swiftly turnover concepts into operations. Diagrammatic modelling commonly applied in engineering in order to represent concepts or reality remains to be an excellent way of converging knowledge from domain experts.

The nuclear verification domain represents ever more a matter which has great importance to the World safety and security. Demand for knowledge about nuclear processes and verification activities used to offset potential misuse of nuclear technology will intensify with the growth of the subject technology. This Doctoral thesis contributes with a model-based approach for representing complex process such as nuclear inspections. The work presented contributes to other domains characterized with knowledge intensive and complex processes.

Based on characteristics of a complex process a conceptual framework was established as the theoretical basis for creating a number of modelling languages to represent the domain. The integrated Safeguards Modelling Method (iSMM) is formalized through an integrated meta-model. The diagrammatic modelling languages represent the verification domain and relevant nuclear verification aspects. Such a meta-model conceptualizes the relation between practices of process management, knowledge management and domain specific verification principles. This fusion is considered as necessary in order to create quality processes.

The study also extends the formalization achieved through a meta-model by contributing with a formalization language based on Pattern Theory. Through the use of graphical and mathematical constructs of the theory, process structures are formalized enhancing the ability to analyse, compare and transform models. In the example domain all possible connections between critical nuclear processes were formalized providing also for probability-based analysis of weapons acquisition paths that will help design objective-based inspection processes.

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Dedication

This Doctoral thesis is dedicated to my mother the late Lirija Abazi.

Introduction

1.1 Overview

The work presented here stretches over several research fields. The objective of the research is to contribute to computer science and knowledge management. Moreover, ahead of the expected challenges, the application domain chosen for the study contributes to the nuclear verification regime presently implemented by the International Atomic Energy Agency (IAEA). The suggested *Nuclear Verification Conceptual Framework* and its realization through the introduced *modelling method* is meant as an instrument for bringing efficiency and effectiveness to the nuclear inspection processes. The work presented studies the specific nature of the inspection processes in a domain that is complex and has a crucial mission of mitigating the risk of nuclear weapons proliferation.

With today's growing challenge of ever increasing need for energy versus the depletion of resources commonly relied upon such as gas and oil, a number of countries are considering refurbishing, reviving or extending their nuclear programme. Table 1.1 shows the number of Nuclear Power Plants (NPPs) undergoing construction in respective countries [3]. The number of already operational plants is almost five times as high excluding other nuclear activities and material worldwide. Some countries with no previous experience are also considering to start a peaceful programme. These changes and the subsequent increase in nuclear production give rise to the already existing concerns about World *security* and *safety*. In addition to the increased presence of radioisotopes there is always the concern of activi-

ties such as illicit trade or production of undeclared nuclear material followed by weaponization [4].

As it is already set forth in the statute of the agency, the organisation has the obligation to verify nuclear material and activities. With these rights and privileges the organisation assumes a great responsibility in assuring the international community on the compliance of all member states with the Non-Proliferation Treaty (NPT). Increased visibility realised in the light of ongoing international concerns puts a great weight on the IAEA to remain relevant and to adjust its ways to the ever changing nuclear context. All this in a politically complex environment while aiming cost effectiveness [5]. This work should find application in the field of nuclear inspections with an objective of discovering new means for preserving relevant knowledge and using it to bring efficiencies in the way *Safeguards* is implemented.

A model-based approach is created using the nuclear verification programme at the IAEA as the example domain to demonstrate the use of models with well defined purpose. The aim is to focus the research on methods that create means for depicting the nuclear verification data and process structures through the use of diagrammatic models. This is expected to help preserve the core knowledge necessary for creating efficient and effective processes that will offset the challenges anticipated with the ongoing nuclear renaissance [6].

The framework which sets forth the conceptual foundation for the approach suggested consist of two levels or layers. The first, top layer is made of domain specific models, each created by modelling languages to describe state's nuclear fuel cycle, nuclear installations, objectives of the inspection, inspection processes and inspection organizational aspects (e.g. roles, assignments etc.). This conceptual layer covers aspects of the nuclear verification and serves as knowledge space that can shape the design of inspection processes. Nuclear processes are modelled and analysed after which safeguards objectives are derived and linked to the inspection processes that lead to their fulfillment. The next layer consists of domain independent models for describing the KM and technology aspects of the verification strategy. By using modelling languages such as PROMOTE and UML knowledge products and supporting technologies in the respective order are identified, modelled and linked to inspection processes. Relying on *Process Oriented Knowledge Management* (POKM), inspection process models are seen as a navigation

Country	Units	Capacity (MWe)	Existing Units	% of Total Capacity
Argentina	1	692	2	3.5%
Bulgaria	2	1906	2	19.6%
China	19	19920	11	1.3%
Finland	1	1600	4	16.0%
France	1	1600	59	54.4%
India	6	2708	18	2.6%
Iran	1	915	0	0.0%
Japan	1	1325	54	17.7%
Pakistan	1	300	2	2.4%
Russia	9	6894	31	10.5%
Slovakia	2	810	4	29.9%
South Korea	6	6520	20	24.1%
Taiwan, China	2	2600	6	12.6%
Ukraine	2	1900	15	25.7%
United States	1	1165	104	10.1%

Table 1.1. Nuclear Power Plants currently under construction; Source: PRIS Database IAEA as of 2010-12-31

mechanism, integration layer or an entry point to knowledge products and technologies modelled through these modelling languages. Inspection processes created are therefore a reflection of domain specific models and maintain the link to domain independent models that describe the knowledge and technology relevant to nuclear verification.

POKM is seen as a mechanism for managing and provisioning knowledge products. It is considered to be an approach that can operationalize process knowledge hidden underneath business processes. With the IAEA inheriting the process engineering principles and adopting common practices under the umbrella of process

and quality management the goal is to have existing methodologies and technologies within the organization integrated under a process-oriented and model-based framework. With the aim of establishing an integrated view of the future organization a conceptual framework based on inspection, knowledge management and technology principles is introduced. This conceptualization serves creation of process models that integrate information structures across the Department of Safeguards. An approach, that is knowledge driven, process managed and aligned across all spheres of support and core processes.

The motivation is to find efficient ways for capturing and synthesizing increasing amounts of information in a structured, transparent and repeatable manner and turning the same into knowledge used for making process design decisions. This is particularly important in this phase of nuclear safeguards where criteria based evaluation of states verified is becoming part of the past. Safeguards criteria will continue to be applied however there is an increasing presence of qualitative information under the so called *Information Driven Safeguards* (IDS)[6].

To tackle some of the challenges previously discussed, the proposed solution is to use models, namely diagrammatic models to depict different views considered in the department of Safeguards when designing inspections. These artifacts are integrated into a *verification knowledge space* which represents expert knowledge of nuclear processes and subsequently the inspection processes made explicit with models that can provide procedural knowledge and functionality to inspectors[7]. The idea is to be able to progress from concepts (e.g. formalized with meta-models) to inspection activities (i.e. instances of process models showing inspection activities at a facility, site or state). All this should be done in a methodical, structured and repeatable manner according to the modelling procedure. Modelling method created is meant to operationalize knowledge into useful inspection process models. Through diagrammatic process models and domain specific models we are able to integrate the management perspective and the verification perspective. The outcome is processes that are efficient but also meet safeguards objectives in order to mitigate any risk of nuclear proliferation.

From the proposed conceptual framework the *integrated Safeguards Modelling Method (iSMM)* is conceived through the integration of a number of meta-models that are conceptualizations of three aspects or perspectives of the framework. In

agreement with the Open Models Initiative a modelling method consists of a modelling technique and algorithms/mechanisms used for processing models. Model types created with iSMM can be used to design verification scenarios and plan inspection activities. The three perspectives of the nuclear verification framework *safeguards, knowledge management and technology* are encapsulated in iSMM. Safeguards as its name implies is represented with models that depict nuclear fuel cycle activities, inspection objectives and the resulting inspection processes. KM perspective serves as a way of representing activities such as acquisition, storage, access and flow of knowledge in support of safeguards. Finally, the technology aspect, is broadly named to represent a range of IT and other technologies supporting safeguards as well as enabling knowledge management. The three perspectives are considered to be the necessary structures for describing the nuclear verification domain.

Modelling activity under iSMM generates content/models with languages which are based on some of the already existing notation and metaphors commonly used by inspectors in the organization. Model types that represent the safeguards perspective of the framework were created for this specific domain whereas the KM and Technology perspectives are represented by domain independent languages that already exist. The KM will be modelled with the existing PROMOTE modelling language[8, 9, 10] whereas the technology related aspects will be represented using techniques such as UML [11].

Starting from a higher layer where modelling languages are used to represent nuclear activities and diversion scenarios in a state, the subsequent layer represents scenario-based inspection objectives that are the link and means of measuring the completeness of inspection reference processes. To be able to externalize some of the domain knowledge into models which can also be processed there has to be a certain level of formalism to which the syntax of the created models adheres to. Models can be used to represent a system under study by solely serving the purpose of "a picture is worth a thousand words" or could be formalised to allow their processing through mechanisms and algorithms. All models are derived from their meta-models imposing on them a degree of syntactical correctness. This said, some models are meant as *Knowledge Management Models* in comparison to more formal models referred to in [12] as *Knowledge Engineering Models*. The former can

be interpreted also by humans and therefore can be incomplete in terms of their capability to be processed by machines. They however still serve an important purpose in the framework by providing knowledge artifacts and context in the inspection knowledge space.

Depending on the processing requirements for iSMM models the level of formalism has to be adequate in order that the intended processing is possible. In some cases formalization with meta-modelling needs to be followed with additional level of formalism that can be achieved for instance with graph theory, petri-nets or graph grammars[12, 7]. In order to formalize the process structures in addition to the data structures represented say with *Nuclear Fuel Cycle Model* (NFCM), creation of a meta-model is in this example not sufficient for processing. In addition to a range of alternatives for formalizing models this study applies *Pattern Theory* (PT) which offers mathematical and graphical constructs that are used to represent rules and possible relations between various nuclear activities modelled with the NFCM language.

The iSMM considers processing of the NFCM used to represent *acquisition paths* of nuclear material that can be used to attain a nuclear weapon. As an example PT formalism is used in order to make NFCM processable and offer model-level functionality. The theory offers constructs called generators that can be combined into configurations to graphically or mathematically formalize modelling elements their inputs, outputs, attributes and their possible connections [13]. Configurations can be considered as formalized process structures that can represent a potential acquisition path and can be evaluated or compared. For example as a result of such formalism a general algorithms can be applied to check the correctness/consistency of the model. Compare structures in different countries or its variations over time in the same country. Additionally, specific algorithms can be used to automatically generate say safeguards objectives out of the modelled acquisition path. Finally, the results show potential to have expert friendly models that can be translated to PT language. PT, can serves as an intermediate language that can be further transformed to data structures or other models such as UML. A number of other applications are also possible as a result of the formalism demonstrated that can contribute to future research in the specific domain and beyond.

Results of the research can be validated by an existing procedure at the IAEA

that is based on conceptual grouping of tools and methods for verifying a member state. The so called *State-Level Integrated Safeguards Approach* is an example of a inspection plan which is designed for a state as a whole by finding optimal combination of technologies and methods to reduce inspection cost while maintaining the effectiveness. With the use of the domain specific modelling languages procedures, mechanisms and algorithms are encapsulated into a modelling method. The artifacts created as a result of the modelling activity represent content that depicts a *Safeguards Approach* through the use of diagrammatic models. In addition to domain knowledge that is externalized iSMM facilitates the creation of process models and a verification strategy that considers safeguards concepts, knowledge management practices and use of advanced technologies. By comparing a safeguards approach currently created in the organization as a document to an approach that is model rich easily accessible, visualized, can be processed and queried represents some of the practical contributions to this domain. The result is content that can be used as a *work plan* or an *inspection path* that is agile and documents clearly inspection activities [14]. Moreover, the modelling method and the overall approach suggested can be applied to any domain characterised with complex processes that can not be acquired off the shelf. A model based approach formalized by mathematical means can help easily capture expert domain knowledge and use the same in the designing of core processes.

1.2 Motivation

Knowledge as a subject has different value depending on the context where it is applied. In the private sector knowledge turns into profits and profits maximize the shareholder wealth. Along the financial value attached to knowledge, organizations which are knowledge intensive but exist in a non-profit environment have also realized the importance of preserving, sharing and even creating new knowledge. The IAEA started efforts few years back to help member states preserve the nuclear knowledge they need to maintain the vital nuclear plants. Recently this organization recognized the need for an inward focus on knowledge and its management as a necessary measure to maintain its relevance on the international nuclear scene. Preserving nuclear verification knowledge is important and may

become crucial in holding the non-proliferation regime on its feet. High quality, efficient and credible knowledge-based conclusions are becoming even more important in redefining the role of the Agency. Increasing number of nuclear facilities worldwide combined with the large amounts of information introduce new challenges in ensuring IAEA's role as the institution in charge of providing nuclear non-proliferation assurance. Quantitative information collected in the field as well as qualitative information from open source requires ever more knowledgeable staff to turn it into actionable intelligence where effective safeguards is also efficient. Already adopted process oriented view of the organization needs to be utilized not only as a catalyst for increasing efficiency but also ensuring the level of quality in verification work performed by inspectors. Reducing costs at the risk of a proliferation incident is not an acceptable scenario for the IAEA since its implications will always exceed the material loss caused by any existing redundancy. Credibility as the trademark of the organization needs to be maintained at any price therefore a process oriented view should not only encourage efficiency but serve as a mechanism to manage knowledge required for performing inspections activities. In light of this, the research tries to contribute with a conceptual framework and a modelling method in order to streamline verification objectives and management needs. This should help preserve procedural knowledge, ensure design of quality verification activities that are cost effective at the necessary price for reducing the risk of the use of nuclear material for non-peaceful purpose by any state.

1.3 Contributions

This work contributes to the field of computer science and knowledge management. It is dedicated to the work of Safeguards Inspectors faced with the upcoming challenges of Information Driven Safeguards. The model-based approach and the pattern theory formalization language is expected to contribute to any domain where models can be used to make domain knowledge explicit and apply the same for improving core processes in an organization.

Chapters ahead review KM literature and the nuclear inspection domain in order to build a foundation in a form of conceptual framework. Carefully considering information, domain and processing logic the framework serves as basis for for-

malizing nuclear verification data and process structures [7]. Through the conceptually intertwined nuclear inspection information structures and existing process management structures, inspection activities modelled are necessarily knowledge based in contrast to otherwise general reference processes. Design of inspection activities is seen as driven by knowledge requiring more structures than typically necessary for business process modelling. Based on this conceptual foundation the modelling method is created which entails techniques for modelling the domain with languages that help structurize and externalize knowledge necessary for quality inspection. To achieve this in addition to formalizing structures through meta-modelling the research offers an example of a formal language that allows processing of models and application of complex algorithms that can be generic or specific. Inspectors will be able through the use of models to better prepare for, analyse and conduct inspections.

In summary, for the domain studied this work comprises of the following major contributions:

1. Application of Pattern Theory for formalising process structures
2. A conceptual nuclear verification framework which is knowledge based, technology aware and process oriented
3. A modelling method named integrated Safeguards Modelling Method (iSMM) used for representing Safeguards information structures
4. A model-based approach to operationalizing knowledge used for designing, analysing and documenting inspection processes
5. An extension of the Process-oriented Knowledge Management approach with domain specific process models

The work is meant to contribute to the daily work of inspectors with a platform that is knowledge rich (i.e. knowledge base) supporting process orientation for performed inspection activities. Modelling languages defined and used serve as the *lingua franca* for preserving, exchanging nuclear verification information structures for use by future Safeguards.

1.4 Thesis Organization

Chapter *two* consists of a literature review section on KM and specifically on applicable KM strategies for a non-profit organization such as the IAEA and the Department of Safeguards - the verification mission of the IAEA. Various KM methods are used to study the KM in the context of an organization with a very specific and important mission.

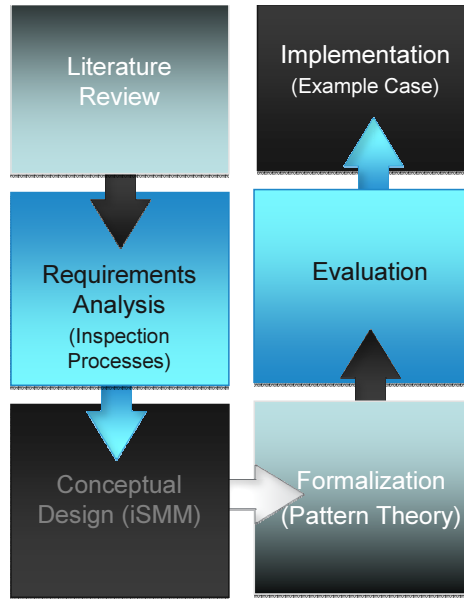


Table 1.2. Thesis Organization

Next Chapter *three*, describes the inspection domain offering an overview of verification concepts as defined in the Safeguards Manual. Furthermore, it describes verification frameworks such as Integrated Safeguards (IS). It attempts to characterize the inspection processes by empirically classifying them in terms of their process complexity and knowledge intensity.

Chapter *four* deals with a model based approaches and presents the verification conceptual framework and its perspectives. The conceptual work is then formalized to be transformed into modelling languages which depict various aspects of the verification domain. Also, objective-driven modelling is considered where Objectives are meant to be the link between domain specific models and inspection

process models. Objectives are seen as criteria which meets the verification obligations derived from the analysis performed on the modelled acquisition path in the fictitious state Ruritania. This chapter concludes also with a brief introduction of the KM modelling language and UML that are domain independent and cover the other two perspectives of the framework.

Chapter *five* attempts to present a way of formalizing modelling languages with the use of Pattern Theory. The example model formalized is NFCM which is used to represent the acquisition path. Since with this language we model all nuclear activities in a state the formalism is applied to define through graphical and algebraic constructs the rules and the logic of combining any two nuclear activities. The example also looks into the potential use of the theory to create probabilistic models that extend the boolean function that only defines the relation between two generators as true or false. The same structure formula can be extended to accept a continuum of values that can characterize relations between modelling elements as more or less probable.

Chapter *six* comprises of the evaluation of the approach. The model based approach and its extension with pattern theory is evaluated in terms of its applicability in the nuclear verification domain. Moreover, the general application of the approach is discussed dealing with complex processes in other domains. Other formalisms such as graphs and Graph Grammars are considered. Furthermore, PT evaluation is provided by comparison to the Petri Net formalism.

Chapter *seven* offers some of the technical details necessary for the implementation of modelling languages using the ADOxx framework. An overview is provided of the classes implemented and the repository of models which are defined in the previous chapters. Moreover, an example case is shown for a fictitious state of Ruritania. Models generated to represent a state-level Safeguards approach in this state is exemplified.

This thesis is concluded with chapter *eight* offering an outlook of future research which this work leads and contributes to. Appendix A offers a glossary of terms whereas Appendix B documents the script for the notation of the modelling language Nuclear Fuel Cycle Model.

Knowledge Management and Nuclear Verification

2.1 Nuclear Knowledge Management

Knowledge Management efforts within the IAEA commenced several years ago. They were traditionally directed outside the IAEA with an objective of supporting nuclear knowledge needs of member states.

The NKM efforts at the IAEA were focused mainly on preservation of knowledge that exists in the nuclear community across member states facing the reality of the ongoing nuclear expansion met by the generation change amongst nuclear experts [15]. By contributing to educational programmes the objective is to preserve, create knowledge in support of the development of peaceful nuclear technology.

The four discernible elements of Nuclear Knowledge Management (NKM) at the agency are [15]:

- Enhancing Nuclear Education and Training
- Preserving and Maintaining Nuclear Knowledge
- Pooling and Analyzing Nuclear Knowledge
- Promoting Policy and Guidance for Nuclear KM

The focus of IAEA's activities from the start remained mainly on preserving nuclear knowledge by enhancing the education and training systems in the field nuclear knowledge. In 2002, the IAEA started implementing a special sub-program known as Nuclear Knowledge Management (NKM). The focus of the subprogramme was to develop guidelines for NKM. Such guidelines are meant to help networking the nuclear community and coordinating education and training so that existing knowledge is transferred to the next generation of scientists and institutions [15, 16]. In its medium term strategy covering 2006 until 2011 the agency puts increased emphasis on nuclear knowledge management as an important part of its international mission. With the increased aspirations for energy independence by states the demand across the globe to further capability of peaceful nuclear energy is expected to increase [6]. This strategy sought by new nuclear states will create a nuclear knowledge demand. Under the present context and vision the IAEA organizes its strategy around three broad pillars: Technology, Safety and Verification.

IAEA's medium term strategy was adjusted due to the reality that nuclear power is more so an option feasible in meeting energy demands by member state committed to remain efficient, safe, secure and clean, and not contribute to proliferation [17]. In this research we will focus on knowledge management in the domain of nuclear verification implemented by the inspectorate. The IAEA organizational structure consists of several departments one of which is the department of safeguards responsible for the verification programme. The research will study on the knowledge management initiatives relevant to the nuclear inspections and the verification domain where knowledge management and engineering can contribute to the information driven safeguards.

2.2 Safeguards Challenges and Knowledge Management

The International Atomic Energy Agency (IAEA) in the last decades has been the international authority in matters of nuclear verification. Traditionally, the international safeguards regime was mainly concerned with the correctness of declara-

tion of nuclear material and activity provided by member states regularly. Member states obliged with their safeguards agreement periodically report their inventories of nuclear material which is then verified through on-site inspections. These safeguarding measures were fortified over time with the introduction of strengthened safeguards followed by the protocol additional [18]. Knowledge management in this study benefits from, however it is not related to the nuclear knowledge management programme discussed before. An effort to internally improve knowledge management within the inspectorate may also contribute to the nuclear knowledge management programme however its focus is not on managing knowledge at nuclear facilities instead it is focused on leveraging knowledge management and engineering concepts and technologies specifically designed to support the verification process. This effort is geared towards researching internal measures that should support IAEA's operations divisions in the department of safeguards.

2.2.1 Integrated and Information Driven Verification

Nuclear inspections and other related activities are complex and knowledge intensive. This amplifies the importance of knowledge management as a tool for increasing efficiency and effectiveness of knowledge workers. The intention is not to disclose any operational details and the information presented here is subject for clearance by the department in accordance with information security policy. The descriptions provided ahead should give sufficient background for the reader to place the research in context and help understand the application of research contributions in practice.

Under the so called traditional safeguards the IAEA was focused on verifying the correctness of state declarations. Nuclear material movement within the state and between them is accounted for and matched through a well defined inspection regime and criteria. This includes regularly scheduled inspections with an objective of verifying that nuclear material is not diverted and all material is exclusively for peaceful purposes. Verification measures were boosted with the strengthened measures proposed by the IAEA in 1995. Since some of the measures required additional authority a comity was formed to negotiate a standardized model for such an authority. The result was the additional protocol model [18]. Figure 2.1

shows how Safeguards has evolved since 1991.

With the introduction of the so called strengthened safeguards followed by the Additional Protocol model (AP), IAEA was provided with better means to verify state declarations in terms of their correctness and completeness. This milestone has lead to increasing amount of information. The traditional approach of implementing safeguards was focused on ensuring that declared nuclear material is not being diverted for non-peaceful use. By using broader range of information the state's nuclear programme as a whole is considered. In addition to state declarations and information obtained through Agency's verification activities other information is combined from open source as well as other sources. Use of information analysis and tools in harmony with a view of the country as a whole lead to state-level safeguards which is "*information driven*" [6].

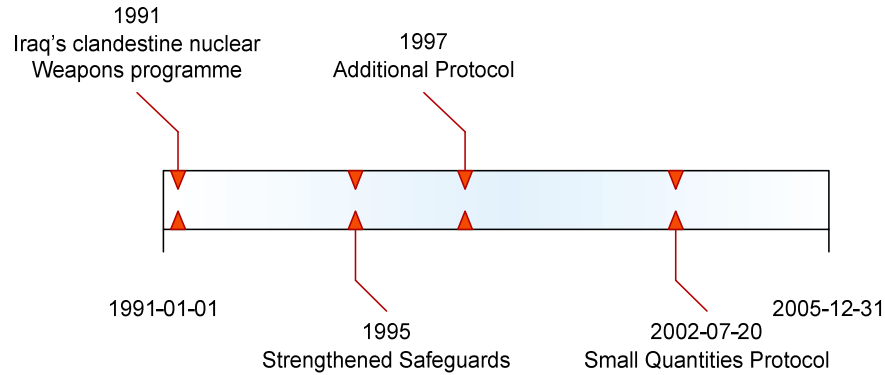


Figure 2.1. Evolution of Safeguards

In order to meet the challenges of the future strengthening of safeguards envisages an Integrated Safeguards approach which aims at integrating traditional and strengthened measures to achieve the optimal combination. Under the comprehensive safeguards agreement verification any undeclared nuclear facilities may exist undetected. With the conclusion of the additional protocol in states with a Comprehensive Safeguards Agreement (CSA) the capability of the IAEA to detect any undeclared activities or material is improved. Such an approach creates opportunities for the reduction of effort on verifying declared nuclear material and

allows for attention to potentially undeclared activities. Such combination of optimal measures are implementable in States where the Agency was able to draw a conclusion that there is no indication of undeclared activity or material reducing the traditional effort on less sensitive nuclear material [18].

The reasoning behind this approach as mentioned before is to introduce measures that represent the optimal combination. Cost cutting measures could be introduced through the use of technology, and tools IAEA has at hand by reducing the number of inspections while in accordance to its legal authority and obligation. The question researched here is focused towards contributing to the field of knowledge management with tools and methodologies in support of the state-level view and integrated safeguards approaches as a part of the future information driven safeguards. It provides a knowledge based support in strengthening the verification process in terms of adaptability, transparency and efficacy through the application of knowledge management and engineering ahead of the expected nuclear renaissance.

Integrated approach stipulates development of the so called state-level view by considering all nuclear and related activities within a state. This differs from the traditional facility-based approach. One of the challenges in developing and maintaining a state-level integrated safeguards approach is continuously evaluating state activities and consolidating large amounts of information stored in databases, discovered through open source or collected through verification activities. Developing, reviewing and evaluating a state level approach is considered a knowledge intensive task by having to consider the overall nuclear programme in a state and any potential acquisition paths acquiring fissile materials with a potential use in a weapons programme.

2.2.2 KM strategy context for nuclear verification

IAEA as one of the international organizations is based on a model that was created and evolved to suit its very specific mission as specified in the statute of the IAEA approved in 1956 article XII which lays out the grounds for the department of Safeguards [19]. The Safeguards project, studied in this thesis, deals with the responsibility of the agency to examine nuclear equipment and technology in mem-

ber states by sending designated inspectors in their territory and verifying reports provided by states. IAEA is financed by regular and voluntary contributions [18]. To better understand the economic model of the IAEA it is important to define its objectives in accordance to the IAEA statute. It is also important to define what makes and organization such as this successful. Since, innovation and profits are not the objective the question raised is what are the fundamental drivers for improving the Safeguards programme. KM efforts undergoing in the organization are an indicator that Knowledge Management is considered to play a vital role in improving its services in the future. In order to align the organizational objectives with KM efforts a strategy based view is considered for devising a knowledge management approach that will support the verification process.

In its short-medium term strategy for the verification mission the IAEA sets forth an objective of providing assurance about the compliance of member states with their obligations. Furthermore, it emphasizes the importance of the effectiveness of the safeguards systems. Through strengthened measures it should continue to increase its capability of detecting undeclared nuclear material. Also, provisions for integrating new types of information in an effective and efficient manner into the state evaluation process. Also, to remain ready for the current arms reduction initiative[17].

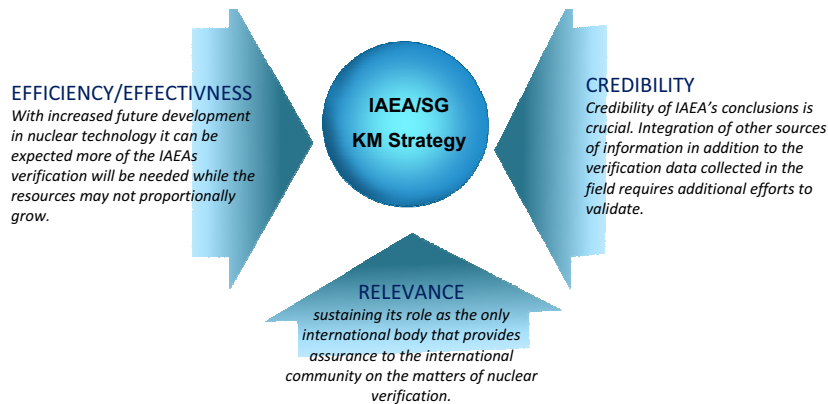


Figure 2.2. The three dimensions of the suggested IAEA strategy that should be considered in devising the KM strategy for the organization and more specifically the Department of Safeguards

Competition or a competitive environment cannot be completely excluded as

a challenge for an organization such as the IAEA. However, it is most crucial to remain relevant. It A related aspect which is equally important is to be credible and finally efficient and effective in meeting all safeguards objectives in light of expected increase in nuclear activities [6]. Its mission has to remain as important as it already is to the international community. It is however not the objective to study the organization and the political context but just so to understand the best suitable KM strategy which can align its mission with KM approaches and tools that can improve the overall performance of the organization and help overcome some of the future challenges.

Next section discusses author's view of the three high-level strategic challenges and their relation to a KM strategy for the verification programme at the IAEA.

Relevance - definition in the Princeton dictionary for the term relevance was having a bearing on or connection with the subject at issue. It a term used to describe how pertinent, how connected or applicable something is [20]. Mission of the verification regime is to ensure peaceful use of nuclear technology and with no real rivalry providing similar services internationally. There are state systems that perform safeguards on the national level however there is no other internationally body that is responsible universally. One of the main objectives is to remain relevant on the international stage. Therefore, the objective of sustaining its role as the only international body that provides assurance to the international community on the matters of nuclear verification. Relevance as a strategic objective compares to the competitive advantage that a private company needs to maintain. In the case of the verification this means continuing to provide to the international community credible assurance that nuclear material is not diverted for non-peaceful use in accordance the obligations of each state under the NPT treaty and its safeguards agreement. Failure to timely detect proliferation occurrence can bring into question the relevance of the non-proliferation treaty and the safeguards systems as its verification mechanism. It is therefore suggested that loosing relevance compares to a company loosing its competitive advantage.

Efficiency and Effectiveness - It is a priority for the board of governors that the verification programme among others at the IAEA continues to improve its response to increasing demands while ensuring cost effectiveness by introducing efficiency [21]. With increased future development in nuclear technology it can be

expected more of the IAEAs verification will be needed while the resources may not proportionally grow.

Credibility - It is not often enough for the department of safeguards to provide evidence about any undeclared activities discovered. Such evidence has to be also credible. With increased efforts to integrate new information in the state evaluation process it is becoming more challenging than ever to synthesize and derive conclusions that are based on facts that support the evidence. Under the information driven safeguards the use of satellite imagery, open source information has shown to be a powerful tool in strengthening safeguards measures. Integration of other sources of information in addition to the verification data collected in the field requires additional efforts to validate the information and reach conclusions on the states nuclear activities. Credibility is therefore another important part of the verification strategy.

The above strategic challenges for the verification regime were derived from the medium-short term strategy as an attempt to steer the KM strategy.

2.3 Strategy-driven Knowledge Management

To have an overview of the knowledge management requirements for nuclear verification programme we start with a top-down view of the organization. The starting point is the strategy which can be used to drive the knowledge management strategy. In some literature KM Strategy is referred to as Knowledge Strategy mainly focusing on profit making entities. For example, the two known strategy based approaches proposed by Zack and Hansen for generating a KM strategy may not be fully compatible with the model of an organization such as the IAEA and especially its verification arm. It is however possible to inherit some of the principles and adapt the two approaches. By combining the economic aspect [22] and knowledge resources required to close any strategic gaps [23] the next section provides an overview of the IAEA verification objectives and potential KM strategy.

Development of a KM strategy begins by defining the business strategy and goals. The question posed here is what should the right strategy for Knowledge Management be in an organization which does not necessarily operate in a such a competitive environment and how do benefits of KM materialize. The govern-

mental sector, which perhaps resembles and is more similar to an international organization such as the Agency, can be used as a starting point and basis for comparison. However, it has to be noted that even there the two differ since in comparison international organizations, government sectors too have a direct relation with their customers, namely tax payers. International organizations are financed through member states contributions and in return the Agency provides services one of which is assurance of non-proliferation. The "way of doing business" can only be partially compared to business *modus operandi* in the profit making sector.

Although the IAEA may not face the same challenges common to the private sector it has challenges of its own created by the environment and reality it is surrounded by. A status equivalent to *competitive* is remaining *relevant* for an international organization such as the agency. Instead of increasing market share an international organization may need to increase its influence so to best justify its mission. IAEA and similar organizations also run based on a certain economic model. Hansen et al claims that the way to build KM strategy is to base it on company's economic model [22]. Michael Zack equally believes that organizational strategic context helps to identify knowledge management initiatives that can support the organizational mission, strengthen its competitive position, and create shareholder value [23]. Both Hansen and Zack propose a top down approach in devising the KM strategy. Hansen proposes that KM initiatives are directly linked to the economies of reuse serving as the basis for creating any KM strategy. Both approaches emphasize the linkage between the organization's purpose and objectives to its KM initiatives. As it is the case most of the companies focus on the digital capture, storage and distribution of knowledge failing to align it to the organizational goals [24].

The two strategy driven approaches introduced offer guidance in developing strategic knowledge however differ in what drives them.

In literature there is a number of approaches that offer guidance in creating a knowledge management strategy by aligning it to its business strategy [22, 23, 25, 26]. A comprehensive summary of approaches is presented in [27]. Knowledge is considered to be a strategic resource therefore organizations ability to capture, store, apply and share it leads to better performance and therefore competitive

advantage [23]. Strategy is defined by Princeton as "an elaborate and systematic plan of action". Such a plan gives direction relative to the current position of a company or organization. Knowledge strategy remains to be one of the important functions of today's knowledge organizations. To devise a strategy there has to be a focus where knowledge assets are the most needed or can add the most value for an organization to gain competitive advantage, become a market leader or in the case of the IAEA improve and extend its mission. In literature knowledge management strategy also referred to briefly as knowledge strategy has many foci as seen by researchers and practitioner. Karl Wiig groups KM strategies in six groups based on the strengths and nature of the organization [28]. Similarly along those lines Day and Wendler offer a practitioner's view and mention five knowledge strategies implemented by large corporations [26].

The two main views considered in devising a verification KM strategy are those introduced by Zack and Hansen. One is known as the customer view focusing on the customer and the product whereas the second view is more of a management view where knowledge as a resource is to employed in reducing and strategic gaps.

2.3.1 Customer/Product View on the Knowledge Management Strategy

Hansen, in his approach for strategic KM (or strategic knowledge) links the economic model of the organization to a customer and product based KM strategy. The emphasis is on the value that the KM adds for its customers. The codification strategy is applicable to organizations that can reuse knowledge whereas the personalization strategy is applicable to those that provide highly customized products[22]. One approach is to focus on the storage, indexing, accessing of knowledge, which is referred as codification whereas the second approach is to focus on the person-to-person means and social networking attributed with the term personalization. The two approaches of codification and personalization are not mutually exclusive however it is recommended that one represents the primary strategy with the other strategy supporting it. With codification the emphasis is on capturing, storing explicit knowledge which can be reused to achieve efficiency, and quality of standardized products provided to the customers. On the other hand the personal-

ization strategy is based on person-to-person knowledge flow that is necessary for services such as consultancy that are customized for the customer. It is therefore the approach from Hansen sees strategic KM from from the customer perspective. Profile of the customer and the type of product or service determines the choice between a personalization and codification strategy. The origins of the codification and personalization strategies are from the epistemological separation introduced by Polany in 1967 who identified the two aspects of knowledge, namely tacit and explicit knowledge. In terms of the KM strategy and the approach in favor the two aspects were aligned to the Gilbert Ryles' "knowing what" and "knowing how" [29]. Knowledge held by individuals in a non-written, explicit form is referred to as tacit knowledge. In 1995 Nonaka presented methods of converting or transforming tacit knowledge to explicit knowledge although Polany indicates that some tacit knowledge will always remain.

2.3.1.1 Verification Information Products

Regularly the IAEA is obliged to report to the board of governors on the verification activities. These reports are written documents issued on the subject state provided of an exceptional situation such as Iran, or Iraq in the late 90s. These products are result of several knowledge processes with the organization in cooperation with the state and other institutions. They represent synthesis of quantitative information collected in the field combined with qualitative information collected through satellite imagery and open source depending on the legal authority given to the IAEA. After being reviewed by experts in the field and after considering state specific data (political context, past activities) a report is prepared for the board [18]. Other reports created and sent to the member states are statement of inspection activities (90a, 90b) or in some cases states are informed of design information verification and examination activities. Moreover reports sent to a state informing about CA activities (10a, 10b) [30].

In addition to the frequent reports and ad hoc reports explained above the main information product generated by the IAEA is the Safeguards Implementation Report known with its abbreviation SIR. This report is generated every year and it covers all states under with a safeguards agreement. A report on the obligatory compliance by the state is created detailing any failures to comply since the last

SIR report. Summarized information on the status of identified issues is followed by details concerning the state or group of states in question. In comparison to the SIR report which is confidential information, the SIR technical report is considered as classified information.

2.3.1.2 Product-based Strategy

Looking at the IAEA and the verification programme from Hansen's angle it is important to define who the customers are and what are the products and services offered. Some of the identified products and services by the department of safeguards are listed as attributed by the type of KM strategy as described by Hansen. For example the Safeguards Implementation Report is based on the verification data and results from the field and can be considered to imply a codification strategy as best suitable to support it. This in comparison to *Safeguard Approach* which is designed for each state and is customized to the state in question would lean more towards a personalization strategy using the characterization from the Hansen framework. It is recognized that any knowledge strategy cannot exclusively support one of the two approaches however emphasis is given to one. Classification of the strategy by end results is also apparent in Treacy and Wiersema's value disciplines [31]. It suggests that an organization can excel at one or most two value areas; customer intimacy, product leadership or operational excellence. These values can be used in having a focused and well placed KM strategy.

Table 2.1 provided, indicates that most of the IAEA products created under the traditional safeguards require codification strategy by storing, indexing and accessing quickly quality information presented to the Board of Governors. On the other hand customized products such as *SG approaches* and *ad-hoc reports* require knowledge that cannot be easily found in explicit form. Such products represent more ambiguous situations which are politically sensitive and require knowledge of a wide range of nuclear activities a particular state may be involved.

Any strategy, including a knowledge strategy has a dynamic component the present knowledge strategy for the verification appears to be mainly on the codification side of the knowledge spectrum however personalization required is also not minor therefore requiring a strategy that balances both. There appears to be a correlation between the way of working under *Traditional Safeguards* and the po-

Information Product/Service	Description	Type of Report	Knowledge Strategy
Reports to the BoG on verification activities	Written documents on the subject state provided for exceptional situations (e.g. Iran, Iraq etc.)	External	<u>Codification and Personalization</u>
Safeguards Implementation Report (SIR)	A periodic report generated yearly detailing the compliance of states since the previous SIR report	External	<u>Codification</u>
Statement on Inspection Results (90(a)) Statement	A formal report sent to the State after each inspection	External	<u>Codification</u>
Statement on Conclusions (90(b)) Statement	Report containing technical conclusions reached through verification activities.	External	<u>Codification</u>
Report on design information examination and verification	Letter sent to the state whenever a DIV/E is performed	External	<u>Codification</u>
SG Approach	It can be facility based or state based. It represents the collection of measures to allow the IAEA to meet its SG objectives/	Internal and External	<u>Personalization</u>
IAEA Annual Report	Report submitted by the IAEA BoG to the GC of the IAEA. It contains the Safeguards Statement	External	<u>Codification</u>
Statements under and Additional Protocol	10(a) is the report informing the State about the activities performed under AP. 10(b) is to inform the State of the results of activities in respect to any questions and inconsistencies	External	<u>Codification</u>
State Evaluation Report (SER)	Recommendations that cover of concerns specific to a state	Internal	<u>Codification and Personalization</u>

Table 2.1. List of some of the IAEA reports for which Safeguards is responsible. Using Hansen’s approach of developing a strategy based on the customer and the type of product an attempt is made to match IAEA’s information products with one of the knowledge strategies.

tential knowledge strategy. The latest trend under the integrated and information driven safeguards can be said still relies on the codification strategy however more and more it will need to adjust to the personalization strategy according to the type of knowledge required and activities necessary for providing services based on real-time synthesis (conclusions) on information rather than reuse of existing knowledge.

Based on the approach [22] some of the questions to be asked in order to discover the choice of the two broad KM strategies are:

- Do you have standardized or customized products?
- Do your employees use tacit or explicit knowledge to solve problems?
- Do you have a mature or innovative products?

The table shown attempts to summarize safeguards products and services in order to better understand the applicable knowledge strategy broadly grouped as codification and personalization by Hansen. Once again this framework was created for firms in the private sectors however it gives a an overview of verification

related products and how they relate the knowledge approach and overall strategy. The most left column lists a number of information products and services for which the Department of Safeguards is responsible. Most of them represent reports which can be broadly classified as internal and external based on the intended audience[32]. The strategy that follows each product is the based on two main questions:

1. Is this a periodic report generated by reusing codified knowledge or does it require analysis of vaguely defined knowledge?
2. Is it mostly based on written documents and data collected or does it require mostly expert knowledge not available in written form?
3. Is it a periodic report or special adhoc report?

By answering these questions an overview of the organization and the knowledge strategy is provided along the lines Hansen attempted with for-profit firms. As mentioned before, often there is no clear link between the services and the customer or the member state as the IAEA is sponsored by member states and it serves the international community as a whole.

It can be noted most of the products require a codification knowledge strategy since they are based on the principle of codifying, storing and disseminating of knowledge that is reused in order to provide the service. Ad hoc reports which are generated for special cases by definition rely more on expert tacit knowledge since they deal with a unexpected situation for which knowledge may not be readily available for reuse. Furthermore, the Safeguards Approach was chosen to require the personalization strategy since each approach is created specifically for a state and its nuclear programme considering also information sources other than synthesis of data collected during the verification. In some cases Safeguards Approaches are simple and are prepared for individual facilities based on a model/template therefore relying mainly on codified knowledge. Also, this products in terms of the audience is both external and internal since the approach is agreed by both, the department and the state.

2.3.2 View of Knowledge as a Strategic Resource

Also in agreement with Morten T. Hansen that strategic knowledge should be based on the strategic vision of the organization, Michael Zack presents a framework which is more seen from a resource management view. For example, by following the organizational strategy and performing Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis using Porter's five forces framework organizational strategic gaps can be identified. Strategic gaps represent the distance between what the company has planned and where it stands at present. According to the author this gap is directly related to the knowledge gap between the knowledge resources a company has and should have to fulfill its strategy[23]. By identifying these gaps through analysis of the company and by mapping the knowledge in the company, weaknesses can be identified. Such weaknesses can then be dealt with using a relevant KM strategy.

Zack claims that key to success is a resource-based view of the company and goes forward to identify components of the KM strategy. Depending on how well the KM supports the organization, knowledge is classified into core, advanced and innovative [23]. Depending on knowledge gaps being internal or external versus the competition an organization can be exploiter and explorer in the respective order. This is a less applicable characterization for the agency as it is meant to measure the gap vis-a-vie the competition. Moreover, another view of knowledge sources can be internal, external or boundless knowledge. Internal knowledge may reside in peoples heads, documents or procedures in contrast to external knowledge which can be sourced from outside the organization such as publications, universities, government agencies and so on. This aspect is important in identifying the degree a organization depends on knowledge resources laying within the organization or those to be sought externally. Based on the strategy of the company, the sources of knowledge it depends on and the type of knowledge it needs companies are classified as aggressive or conservative. Such examples of knowledge management strategy are largely meant for profit-making entities as they mostly utilize KM as means of remaining competitive through innovation and productivity. The next section will try to look at the Agency's knowledge management strategy for the verification domain using a hybrid of the previously mentioned approaches. A discussion what the perceived knowledge gaps, the type of knowledge it requires

Strategic issues	Type of knowledge	Closing Knowledge Gap through	Source of Knowledge
Supporting the global non-proliferation regime.	Core	<u>Exploitation</u>	Internal
Coping with the nuclear expansion and increasing Safeguards workload	Advanced	<u>Exploitation</u>	Internal
Safeguarding advanced nuclear reactors and innovative fuel cycles	Innovative	<u>Exploration</u>	External
Taking on further nuclear verification mission	Advanced	<u>Exploration</u>	Internal
Managing increased public attention, confidentiality and transparency	Core	<u>Exploitation</u>	Internal
Building political support for the IAEA safeguards and verification	Core	<u>Exploitation</u>	Internal
Ensuring sufficient legal verification authority	Core	<u>Exploration</u>	Internal
Improving cooperation with states	Core	<u>Exploitation</u>	Internal
Keeping abreast and making used of scientific and technology innovation	Innovative	<u>Exploration</u>	External
Resourcing the IAEA's nuclear verification mission	Advanced	<u>Exploration</u>	External
Improving the way the department works	Core	<u>Exploitation</u>	Internal

Table 2.2. Safeguard Strategic issues presented using the strategic gap framework from Michael Zack

to remain relevant in the international community or commonly referred to as competitive. This involves effective and efficient safeguards supported by a proper knowledge management strategy, which is a prerequisite for a successful mission in a knowledge driven organization.

Some of the main questions to ask in this approach are:

- What are your knowledge gaps
- What are your internal knowledge gaps
- What are your external knowledge gaps (compared to competition)
- Compare your dynamic learning capabilities

Based on the strategic framework for mapping knowledge the organizations knowledge gaps are seen relative to the competition. In the case of the IAEA this

is not applicable however identifying the types of knowledge required and how they link to the strategic issues or gaps may still enhance the understanding of what would be a suitable knowledge strategy. On the left, most, column the strategic issues are listed which were discovered during the strategic planning exercise at the department of safeguards (SWOC analysis) [33]. These issues are presented here using Zack's strategic mapping framework. The second column (Knowledge Type) shows the classification of knowledge which can be "Core, Advanced or Innovative". Core knowledge is the basic level of knowledge that will keep a business going however will not give it a competitive advantage compared to its competitors. Advanced knowledge on the other hand is knowledge which can give a firm a competitive edge. Finally, the innovative knowledge is of the type that makes a firm the market leader. To better put this classification in use for the purpose of the verification knowledge strategy it is slightly adapted where core is the basic knowledge for the organization and the verification mission to remain relevant, advanced would increase its credibility whereas innovative knowledge can bring it forward for instance by of extending its mission (i.e. disarmament agreement) and becoming the only authority on nuclear issues.

The classification shown in the table is based on the strategic issues identified and by answering the following questions in order to link it to the knowledge resources:

- What knowledge type would best address these issues in meeting strategic objectives stated in the medium-term strategy?
- Can the required knowledge be applied by exploiting the knowledge resources in-house or it needs to be explored outside the organization?
- Does it require closing a knowledge gap internally or externally (institutions, governmental agencies etc)?

Here an assumption is made that all the strategic issues are linked to potential knowledge gaps that exist. Knowledge gaps that cause the strategic gaps need to be addressed by the knowledge strategy. The table offers an overview of the dependency of the organization on knowledge resources however classified and gives somewhat an orientation for sourcing knowledge resources under the verification

knowledge strategy. Furthermore, it is important to find means of minimize the dependency of the organization of knowledge resources insufficiently available while utilizing knowledge already available in the organization.

2.4 KM Spectrum and Verification Strategy

In addition to the reviewed approaches for creating a knowledge strategy for the verification programme at the IAEA it is useful to create a KM landscape of applications that are presently used or are in development within the department of safeguards. Next figure showing the "as is view" of the safeguards systems and activities is integrated with the product-based and resource-based view of KM strategy discussed earlier. Literature suggests various ways of segregating the KM spectrum however one research performed by Binney comes to mind as the most applicable and general to fit the classification of KM elements in a organization such as the IAEA. He synthesizes the KM activities and related technologies into six categories [34]:

1. Transactional KM – knowledge is embedded in the application of technology. Here the knowledge is presented to the user in the process of completing a transaction
2. Analytical KM - knowledge is created from various data sources by turning it to information which can become knowledge
3. Asset management - Management of explicit knowledge and intellectual property
4. Process-based KM - represents the improvement of processes and working practices.
5. Developmental KM - it covers activities for increasing the competencies of knowledge workers
6. Innovation/Creation KM - includes providing an environment in which knowledge workers as individuals and as a group can collaborate for creation of new knowledge

Aspect	Transactional KM	Analytical KM	Asset Management KM	Process based KM	Developmental KM	Innovation/Creation
KM Spectrum	Case Based Reasoning, Help Desk Application, Order Entry Applications	Data Warehousing, Data Mining, Business Intelligence, Management Information System, Decision Support System	Document Management, Content Management, Knowledge Valuation, Intellectual Capital, Knowledge Repositories	TQM, Best Practice, Quality Management, Business Process Re-engineering, Process Automation, Methodology, Lessons Learned, SIE/CMMI, ISO9xxx, Six Sigma	Skills Development, Staff Competencies, Learning, Training, Teaching	Communities, Collaboration, Discussion Forums, Networking, Virtual Teams, R&D, Multi-disciplined teams
Safeguards KM Applications Spectrum	TCR, Inspection Scheduling System, CIR Mobile, CA Mobile	CIOSP, DSS, NPT DWH, NRTA, Statistical Methods and tools, GIS, Information Analysis, Open Source	LiveLink, SG Document Manager, SG Portal	CMMI, PRINCE2, IRP, QM	ICAS, Training Programme, Seminars, Workshops, Teachings by staff	SG Portal, Discussion Boards, Expert Roster, Novel Technologies, Red Team
Information Products/Services	90a, 90b, 10a, 10b, 10c					
	Safeguards Implementation Report (SIR), State Evaluation Report (SER)					
	SG Approach, Exception Reports					

Table 2.3. as is KM Spectrum of Safeguards KM systems and activities

The table shows an overview of the KM activities according to Binney extended with the application landscape at the Department of Safeguards. Furthermore, a connection is made to the knowledge strategy analysis based on products and services and strategic issues. The spectrum shows how starting from the left the emphasis is on codification and explicit knowledge whereas the other end considers mostly KM activities organized around implicit and tacit knowledge. Implicit knowledge being non-explicit knowledge likely to be codified [34].

The information products and the associated KM activities only give a vague idea on the existing relationship between knowledge management and the actual products of the department. Most of the products are based on the codification strategy therefore rely on transactional, analytical and asset management KM where explicit knowledge is the main contributor to the efficient generation of quality products. The process-based KM is also an aspect which is identified and is considered to be an important component of enhancing procedural knowledge. Other activities which are more dealing with implicit knowledge are equally important and are being increasingly sought for under knowledge activities of integrated

and information driven safeguards [18].

2.5 Process-oriented KM

From the knowledge management strategy reviewed in this chapter there are elements which lead to a codification based approach however there is a great need also for personalization and lots of focus on tacit and implicit knowledge pertaining to the verification programme. It is therefore necessary to develop an approach that represents a balance of activities that are focused on both implicit and explicit knowledge. A known approach for externalizing implicit knowledge while easily managing explicit knowledge through a process view is Process-Oriented Knowledge Management (POKM). The process orientation appears followed by processes modelling represents an important part of identifying knowledge activities and discovering procedural knowledge. It also provides a link to all KM aspects while remaining aligned to the business processes and therefore the business strategy.

The process-orientation within knowledge management was mentioned since the start of knowledge management in the mid nineties [14]. Some years later, there were several initiatives that made process-orientation the major part of the organizational dimension of knowledge management. A list of approaches includes [35] *Income* approach which linked knowledge resources to processes; the *Workware* approach distinguished between tacit knowledge and explicit knowledge in a process, where implicit knowledge is aimed to be expressed in a different notation rather than process sequences; the EULE2 is an agent based supporting system considering knowledge flows as processes; the K-Modeller is a modelling method for knowledge-intensive business processes; the ARIS extension provided additional modelling elements for platforms like Hyperwave.

Two research initiatives studied process-oriented knowledge management very intensively. DECOR [36, 37], was an EU-Project linking ontologies with business processes. The focus was the ontology support of business processes. Furthermore, PROMOTE was an EU-Project providing a holistic modelling language for process-oriented knowledge management based on the business process management paradigm [38]. Since then PROMOTE [39, 40] continuously improved in commercial projects [41] and in the EC-Projects Akogrimo [9], AsIsKnown [41]

and BREIN [8].

Beside PROMOTE that evolved from a serious research initiative towards a commercial product. KMDL is another approach that reached commercial level today. KMDL focuses on key processes and provides a dedicated model languages for the analysis of processes [42].

Overall process oriented knowledge management has three view-points:

1. The process is seen as content. Usually this is managed by traditional business process management approaches that make the implicit know-how of an organization explicit in forms of process models.
2. The process is seen as the entry point and as an integration platform of knowledge management. The majority of process-oriented knowledge management approaches focused on this view-point, as it raises the effectiveness of knowledge management. Processes of the daily work are analysed, and supported by knowledge management.
3. The process is seen as the management approach for knowledge. As are business processes managed the approach evolves to the management of the KM activities from a process-oriented standpoint.

For the implementation of inspection models and a knowledge management approach for the department of safeguards the PROMOTE approach was chosen. All three views of POKM are interesting in the context of the inspection modelling framework. The inspection processes to deter the potential weapons acquisition are considered knowledge intensive and will therefore be supported in a process-oriented with knowledge resources. PROMOTE covers the knowledge management perspective of the inspection modelling framework presented later on.

2.6 Knowledge Engineering and Knowledge Management

The outcome of the modelling activity does not have to lead to a creation of a knowledge system typically the case with approaches such as CommonKADS [43].

The harmony between these perspectives leads to the inspection modelling as an activity for documenting conceptualizations of the verification domain on a platform that allows primarily analysis of inspection processes as a result of identified safeguards objectives for a specific state. To achieve this also a level of formalism is required to empower the use of models in the framework. An example would be the use of algorithms to validate the knowledge or in practical terms validate models that represent a conceptualization. Such a formalism is possible also through pattern theory providing us with algebraic constructs that can be used for example to check the consistency of models both syntactically and semantically.

Knowledge engineering is defined as the task of building knowledge systems. It is also considered synonymous with the modelling activity today. However, this definitions and terminology inherits to a great deal the work of past decades where information systems were segmented from the knowledge system on the basis of their purpose. Presently most information systems are partially knowledge system something that has followed the natural evolvement of the business and other areas which have seen increase in their complexity.

If modelling as an activity was traditionally related to knowledge engineering in a strict sense this is even more so today. However every system can be at least partially considered a knowledge system.

In literature and practice the two fields of knowledge management and engineering are seen as two quite separate fields that deal with difference problematic regardless of the knowledge focus they have. One is seen as a management approach where knowledge is viewed as a resource whereas the second one deals with transferring of knowledge to systems. If knowledge management is the field which deals with methods, tools and approaches that can best management knowledge in the organization it can be said that this field also is related to knowledge engineering as a knowledge providing instrument. Does knowledge management mange efforts such as knowledge engineering? No, however since KM is considered to be a socio-technical system the technical part may involve knowledge engineering and therefore is in directly related to KM.

In the case of inspection modelling the idea of knowledge management in the department of safeguards requires efforts that deal with issues of knowledge man-

agement and are supplied with knowledge objects conceived through knowledge engineering approaches such as modelling. Use of diagrammatic models to represent concepts of safeguards does not only have to be seen as an effort for creating specific artefact for the department that can be used in designing and implementing information and knowledge systems. Quite the opposite they can serve as content for documenting and visualising safeguarding concepts contributing to the working level as knowledge space for designing and specifying inspection processes to best meet safeguards objectives. Under the open models initiative the use of modelling methods considers components (language, procedures and algorithms) which represent chunks of a packaged knowledge with functionality to solve repeatable and single instance problems.

As it is the case with inspection modelling the objective is to contribute to the management of knowledge however through a knowledge engineering approach which is a component of a socio-technical environment. Models used under the framework represent conceptual integration of sub-domains of verification which lead towards verification approaches that are coherent, effective and cost aware. Additionally, this conceptualization can be followed by a level of structure and formalism that can align such approaches to with the technology in the department. As discussed in the previous section an effective way of a managing and accessing knowledge is through a process view. It is therefore that POKM is applied here as an approach.

Where the paths of KM and KE in this thesis cross is POKM seen as a knowledge management approach which is model based. Models here are used for representing business processes, knowledge processes as well as other structures that a part of an approach. Models are artefacts that offer guidance and content for tracking and managing the implementation a knowledge management. On the other hand use of models and modelling as an activity is synonymous to knowledge engineering where they are used to capture concepts from experts eventually transformed to data structures and rules of a knowledge based system. The common element between POKM and KE here is therefore a model as a representation or content that can support knowledge management provisioned through knowledge engineering techniques. Inspection models which are domain-specific are integrated with the PROMOTE modelling method in order enable and sustain POKM.

Moreover, knowledge represented through models with certain level of formalisms represent conceptualizations that can be processed to offer functionality for both implementing systems and improving the performance of business [12]. Based also on the principles of MDA/MDE the use of models is also favoured as an approach for abstraction in developing information systems by documenting requirements of a system and contributing to the analysis, design and source code generation. Very much like the activity that use to only be present in the development of expert systems.

In the case of the inspection modelling, models created based on the modelling method are integrated into a common framework which supports knowledge management by having process models as an entry point while also entailing knowledge engineering principles for creating, extending and maintaining modelling methods in support the POKM. "Knowledge assets are those bodies of knowledge that the organization employs in its processes to deliver value" [43]. Models representing technology are a part of the framework to enable the alignment of KM through KE and the technology available.

The framework provisions for engineering modelling methods as specified in [7] to extend the ability of creating meaningful models that can be used in implementing POKM as a management approach and supporting it with models that represent knowledge content and can be used to build knowledge based inspection processes specific to the nuclear verification domain. An example of an important conceptualization is the so called SG approach which represents a conceptual roadmap to ensure that the implementation of safeguards in a state or facility covers all possible nuclear weapon acquisition paths. An approach can be designed by using inspection models that are integrated with the models of the PROMOTE approach where the PROMOTE can be seen as knowledge provisioner or a console application that steers the inspection management. This fusion of models that have been classified in [44] by *use* and *form* represent a union of process oriented knowledge management and knowledge engineering techniques.

2.7 Conclusion

Since the framework from Michael Zack mostly is targeting the strategy vis--vis its competition we need to look at the same from the safeguards perspective to ensure that agencies mission remains relevant. What makes it relevant in comparison to a private company is not so much competitive advantage in terms of its product but rather the quality of its products (introduced earlier) considering that there is no other organization offering such services. So, the quality of the services provided by the IAEA about verification is a dimension that needs to be reflected in the knowledge management strategy. For a knowledge organization such as the IAEA, remaining relevant will mean that no state diverts nuclear material under its watch. Few such occurrences will question the existence of such an entity under the current principles of verification. Therefore maintaining relevance as a organizational strategy needs to also be a part of the strategic knowledge management. Finally, in terms of the knowledge management strategy, the inspectorate at the IAEA needs to not only know more (usually the relation with the competition in the private sector) to eliminate its competitors but it needs to know better and know faster. There is a timeliness element involved in the model of the IAEA which is important as it is in the private sector for rather "aggressive companies". Should the organization know too late about existence of a nuclear material diversion as a result of negligence there are very few measures that can repair this damage caused. Efficiency and effectiveness are therefore the other important component of the knowledge strategy that can contribute to the strategic objectives of the organization.

Inspection Concepts and Requirements

3.1 Introduction

This chapter provides an overview of inspector activities and regimes for implementing Safeguards in IAEA member states. The type of activities, frequency and scope of activities are based on the safeguards agreement between the agency and the particular state. The safeguards agreements are commonly based on the Comprehensive Safeguards Agreement (CSA) model referring to the Information Circular (INFCIRC) 153 type agreement which was later extended with the protocol additional (INFCIRC 540). A group of states such as India, Pakistan, Cuba and Israel have are safeguarded under a special agreement INFCIRC 66. The chapter presents the inspection types and activities documented in the Safeguards Manual and Safeguards Glossary and provides an overview of the same from a knowledge management perspective. Inspection processes are evaluated for their complexity and knowledge intensity based on the method introduced by Eppler[2]. Based on an empirical study conducted with safeguards inspectors the objective is to identify inspection activities that deserve the most attention and serve as requirements.

3.2 Nuclear Inspections

The formal definition of inspection is provided in the Safeguards Manual [45] This specific type of inspection represents a number of activities which are performed by inspectors at a nuclear installation in order to verify material that was previously declared by a state. Subject to the agreement with the state the IAEA inspector verifies that material and locations are used solely for peaceful applications.

According to the Safeguards Manual there are two main types of installations: Facilities and Locations Outside Facilities (LOFs) which are a subject to verification depending on the safeguards agreement in force. Installations are further categorized as power reactors, research reactors, critical assemblies, enrichment and so forth attributed with a unique code (A, B, C etc.) described in [30]:

3.2.1 Inspection Types

Depending on the type of agreement between the states and the IAEA there are different types of inspections that can be carried out accordingly. Official definitions and details can be found in [45] however this section will only summarize each:

Initial Inspection: is a inspection carried out in accordance with the safeguards agreement. Its objective is to verify that the facility constructed is in accordance with the design details provided to the IAEA. This type of inspection will take place as soon as the facility in question is included under safeguards.

Ad-hoc Inspection: Is the type of inspection that can be performed by IAEA inspectors before a subsidiary arrangement with the state has been reached. A subsidiary arrangement represents the document containing administrative and technical procedures explaining how the provisions of the safeguards agreement should be applied [30].

Routine Inspection: This type of inspection allows the IAEA to perform routine inspection at a facility or location outside. It entails verifying that all record are consistent, verify all nuclear material and other routine activities such as audits, examinations, perform measurements etc.

Special Inspection: Such an inspection is normally carried out in addition to the routine inspection effort. It may be that the IAEA requests access to a

location which is additional to the access agreed upon with the state for routine inspections. A special inspection is performed in consultation with the state [45]. They are often carried out as a result of a study or report showing that this type of inspection is desirable.

3.2.2 Inspection Regime

This section discusses various inspection regimes. Regime is defined as a set of conditions, most often of political nature. Regime is a model of rule or management. The organization that is the governing authority [20].

Inspection regimes depend on the arrangement between the IAEA and the State. Visits by inspectors can be carried out under one of the following regimes:

Unannounced Inspection: provides the IAEA the right to conduct inspection without advance notice.

Simultaneous Inspection: is an inspection at two or more facilities done within a short period of time. Short enough as to ensure that any borrowing of nuclear material between these facilities would be detected. This is an inspection that requires an approval on case by case basis. The inspections are usually carried in the same day.

Inspection Serving Timely Detection Purpose: is an inspection at which the inventory verification and other activities associated with the timeliness component of the inspection goal are carried out.

Short Notice Inspection: is an unannounced inspection with a short notification agreed with the state/operator of the facility.

Random Inspection: represents an inspection carried out on the principle of random selection; It may be random in terms of timing of the inspection or to the selection of the facility or location to be inspected.

Short Notice Radome Inspection (SNRI): is a routine inspection that must meet the definition of both inspections on short notice and random inspection.

Limited Frequency Unannounced Inspection (LFUA): such an inspection is carried under a safeguards approach which is specifically developed for enrichment plants using centrifuges. Subject to the agreement with the state an enrichment plant can be inspected on short notice.

New Partnership Approach Inspection: an inspection carried out under the New Partnership Approach regime agreed between the IAEA and EURATOM.

3.3 Inspection Concepts

The guiding conceptual framework of modern Safeguards is *Integrated Safeguards*. It represents combination of optimal measures for increasing efficiency and effectiveness. Here cost cutting measures could be introduced through the use of technology, and tools IAEA has at hand by reducing the number of inspections while in accordance to its legal authority and obligation. It is meant to combine measures and activities specifically designed for a nuclear site of a state as a whole. It aims to make the most use of strengthened safeguards to provide the most efficient means to realizing full effectiveness. Next there is will be a brief description of the Safeguards Approach which is the main information product that makes explicit the carefully designed measures for a facility, site or state.

3.3.1 Safeguards Approach

Safeguards Approach is designed to allow the IAEA to meet the applicable SG objectives. It takes into account the features of the SG agreement with a particular state. As defined in /citesgman approaches can be designed for a facility, type of facility or state as a whole under integrated safeguards.

Facility Approach - follows the analysis of all possible diversion paths for facility and the requirements of the undersigned SG agreement. The approach considers what is required by a diverter in terms of facilities and if these are present in a state. Factors considered in the design are facility design features, application of measures of containment and/or surveillance, attributes and accessibility of nuclear material as well as the analytical and measurement methods available to the IAEA. As experience is gained through the verification activities, the approach is modified as required [45].

Under the so called integrated safeguards (IS) there are generic approaches for each facility type. The technical objectives remain the same. Activities to meet the objectives are defined in the model integrated safeguards approach for each

facility type. Such an approach as stated in [45, 18] is based on the premise that IAEA has drawn a conclusion of "non-diversion of declared nuclear material and the absence of undeclared nuclear material and activities in the state concerned."

State-Level Approach (SLA) - Safeguards approach on a state-level is meant to cover all nuclear material, nuclear installations and nuclear fuel cycle related activities in a state. Such an approach implements safeguards measures at all facilities and outside locations in a state that have the AP already in force. IS approaches for each type of facility are combined with the implementation of AP measures, especially complementary access (CA) [18].

The approach has to take into account the state's safeguards evaluation, states nuclear fuel cycle and the interaction between state-specific facilities and other features such as the ability to carry out unannounced inspections in the state accountancy system for accounting and control of nuclear material [45].

3.3.2 Safeguards Criteria and Inspection Goals

There is another component that is a part of the safeguards approach and that is the *Safeguards Criteria*. According to [45] it is used for "planning the implementation of verification activities and for evaluating the results of these activities." Such criteria are applied based on the approach designed as described previously. Criteria for each type of facility under safeguards is defined showing the scope, frequency and the extent of inspections needed to achieve the safeguards objectives. Criteria also defines activities to be coordinated across a state. To maintain the continuity of criteria based evaluation, criteria are also being developed for facilities under integrated safeguards. Moreover, state-level criteria under integrated safeguards is in its workings.

Another important aspect of the verification is the so called *Inspection Goals*. As specified in the criteria, inspection goals are performance targets. These performance goals apply to verification activities for individual facilities and for activities co-ordinated across the state. For a facility inspection goal consists of the *timeliness* and *quantity* components. The quantity component is related to the scope of activities in order to conclude that there has been no diversion or 1 SQ in material balance period. On the other hand the timeliness is attained with periodic

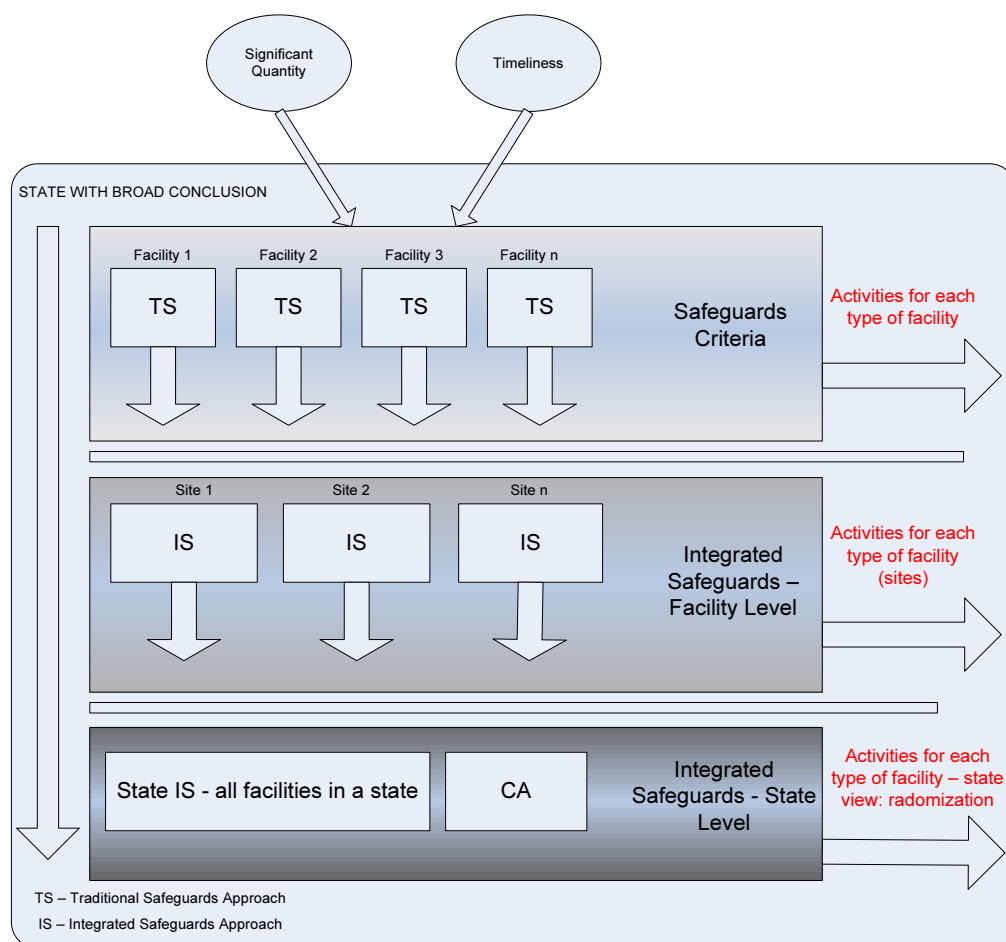


Figure 3.1. Breakdown of the criteria based safeguards and its evolution to integrated and state level approach

activities necessary to conclude there was no sudden diversion in a calendar year [45].

3.4 Inspection Process

The department of Safeguards has identified nine macro-processes. In addition to core there are also management and support macro-processes. The core macro-process which is of interest here consists of Safeguards Planning, Information

Collection and Analysis, Verification and Evaluation processes. In this section processes related to the Verification broadly named as Inspection Process will be summarized. The verification macro-process consists of the following [46]:

- Scheduling verification activities in a State
- Preparing, conducting and reporting Design Information Verification (DIV)
- Preparing, conducting and reporting inspections
- Preparing, conducting and reporting complementary access

This section describes activities as listed in the current SG Manual categorized as general inspection activities. Furthermore, details about the DIV/DIE activity and CA activity will be provided. In the last section an attempt is made to empirically show the knowledge profile of inspection activities using the matrix combining process complexity and knowledge intensity .

3.4.1 General Inspection Activities

Various activities that may be carried out during or in relation with the inspection are:

1. **Examination of Records:** Examination of records may include activities such as examination of accounting and operating records, their reconciliation, comparison of facility records with the State reports etc. (reports the state is obliged to submit to the IAEA)
2. **Verification of Nuclear Material:** Material balance area can be shortly referred to as MBA. This activity is performed since an operator could try to conceal the diversion of nuclear material by understating inventory increases, overstating inventory decreases, or both. The verification performed ensures that such under or over statement take place.
3. **Verification of Non-Nuclear Material and Specified Equipment and facilities:** In some types of agreement the application of IAEA safeguards may include also non-nuclear material, and specified equipment and facilities. The types of material for which safeguards may be requires are those

necessary for the production of special fissionable material subject to the agreement. Examples include heavy water, nuclear grade graphite etc.

4. **Sampling for Destructive Analysis (DA):** sampling and analysis is an accounting verification method. It means taking a representative portion of solid, liquid or gas from an item or batch, selected as a sample for destructive analysis. As defined in [30] Destructive Analysis determines the content of the nuclear material and if necessary the isotopic composition of chemical elements. There is also so called Non-destructive Analysis. DA verification of nuclear material includes taking samples, ensuring the integrity of the sample during transport, packing, sealing and shipment to the laboratory.
5. **Environmental Sampling (ES):** it is an activity that may be carried out during inspections or DIV visits or Complementary Access. ES may also provide confirmation of the declared activities and nuclear material present, but this is usually a secondary objective as the lack of a nuclear signature on an environmental sample should not be interpreted as the absence of a given activity.
6. **Containment, Surveillance and Monitoring Measures:** This activity consists of a set of measures. Containment is defined as those structural features of the facility, container, or equipment which are used, in conjunction with seals, surveillance or monitors, to maintain the continuity of knowledge of items and area by preventing undetected access or movement of items. Seals, together with the containment to which they are attached, constitute containment measures [30]. Surveillance represents the collection of information about locations and movement of nuclear material, equipment or containment by using cameras that are connected to recording devices. These recordings are reviewed by inspectors.
7. **Confirmation of the absence of Unrecorded Production of Direct-Use Material from Material Subject to Safeguards.**
8. **Verification of Operator Measurement System:** The purpose of this activity is to verify the quality and functioning of operator's measurement systems which aims at determining the limits of accuracy of the stated amounts

of material for inventory and inventory changes and thus of the material unaccounted for (MUF). Such an activity allows the IAEA to estimate the measurement errors in order to check that the estimates are in accordance with the design information for the facility and are consistent with the International Standard of Accountancy.

9. **Evaluation of Specific Inventory Changes:** This inspection activity requires that certain inventory changes are verified by the IAEA if the nuclear material amounts involved exceed predefined limits. Such limits are predefined in the Safeguards Criteria. Some examples of inventory changes are measured discards, transfers to and from retained waste, accidental losses, exemptions etc.
10. **Material Balance Evaluation (MBE):** is a tool that entails statistical evaluation of the material balance. In order to assess the correctness of the nuclear material declared by the operator of the facility various components of the material balance are evaluated. This activity is performed in order to detect potential diversion into MUF. To detect diversion into D by operators falsifying accounting records and verifying the operator measurement systems.
11. **Utilization of Safeguards Equipment and Devices:** Various equipment is used to perform inspection activities. In order to use IAEA equipment cost-effectively and ensure the quality of the data collected it is important to practice inventory control and performance monitoring of the equipment. Furthermore, evaluation of the inspection data is an important part of the post inspection activities.

3.4.2 Design Information Examination and Verification

Design Information or shortly DI includes design features for facilities relevant and is used to establish the safeguards approach for a facility by determining the material balance area, (MBA), key measurement point (KMP) and other strategic points. Using design information the verification plan (DIVP) and the essential

equipment list (EEL) is established [45]. Design information is submitted by the state using the Design Information Questionnaire (DIQ).

In order that a safeguards approach is established for a facility a set of measures have to be identified for the implementation of safeguards in order to meet the applicable safeguards objectives. Safeguards approach is based on a) determination of possible diversion strategies and pathways; b) determination of the potential misuse of the facility; c) determination of the appropriate safeguards measures to meet the criteria; d) results of the design examination and verification.

3.4.3 Complementary Access

Where most of the verification activities under the traditional safeguards focus on the nuclear material declared, complementary access plays a key role in deriving safeguards conclusions on the absence of undeclared nuclear material and activities in states with AP in force. Additional protocol is a model designed to strengthen the effectiveness and improve the efficiency of the safeguards system. It is important the complementary access as a tool under AP is carried in accordance with provisions in the additional protocol and in a consistent and non-discriminatory manner.

3.5 Inspection Knowledge Profile

3.5.1 Inspection Process Analysis

The above discussed processes require analysis to identify them as being knowledge intensive or complex. The general inspection activities followed by design information verification and examination (DIV/E) and complementary access (CA) are discussed. Based on attributes of the selected processes the process complexity and the related knowledge intensity will be considered. Using a process-oriented approach where knowledge is derived from a process and is about process Eppler suggests a matrix that classifies processes as [2]:

1. Low process complexity combined by weaker knowledge intensity (**Class 1**)
2. High process complexity by weaker knowledge intensity (**Class 2**)

3. High process complexity by stronger knowledge intensity (**Class 3**)
4. Low process complexity by stronger knowledge intensity (**Class 4**)

From a knowledge management perspective the most interesting processes are those in in class 3. Table 3.1 was adopted form an approach presented in [2] and shows the classification of attributes of a knowledge intensive and complex process.

Attribute	Description	Knowledge Intensity
contingency	The agent activities are contingent because of the numerous eventualities (i.e. dependent if environmental influences)	strong
	The agent activities are defined and outlines (i.e. by process policies) and do not change greatly through environmental factors	weak
decision scope	The agent has several possibilities, how process-related decision can be made.	strong
	The agent has hardly any variety in his activity	weak
half-life	The agent's knowledge is quickly obsolete. The process-related knowledge has to be updated often.	strong
	The agent's knowledge is relevant for a longer time if it is once established	weak
agent impact	The agent has major influence on the outcome of a process.	strong
	The agent has minor influence on the final result of a process	weak
learning time	The agent needs a long time period t acquire the necessary skills for his tasks.	strong
	The needed skills for the agent activities can be acquired fast.	weak

Table 3.1. Attributes used to evaluate inspection activities for their knowledge intensity. Adopted from Eppler[2]

Agents described in the tables 3.1 3.2 can be humans, communities or information processing machines. Since processes may be knowledge intensive and at the same time simple or complex the evaluation considers also another dimension, namely attributes of a complex process. As it was the case with the knowledge intensity, table 3.2 shows that attributes which characterize a process in terms of its complexity. Number of steps involved, number of involved agents and interdependencies give a closer look at processes which are more complex and therefore require more procedural knowledge. Processes identified as core within the department are broken down to inspection activities which are taken from the SG Manual. In addition to so called general activities, complementary access and

DIV were considered. Data was based on answers collected from inspectors where knowledge intensity and process complexity for each activity was attributed as "Strong" or "Weak" and "High" or "Low" in the respective order. The objective is to identify which knowledge is crucial for the success of these processes. How can that crucial knowledge be managed and systematically exploited [2].

Attribute	Description	Process Complexity
process steps	The agent activities are contingent because of the numerous eventualities (i.e. dependent if environmental influences)	high
	The agent activities are defined and outlines (i.e. by process policies) and do not change greatly through environmental factors	low
involved agents	The agent has several possibilities, how process-related decision can be made.	high
	The agent has hardly any variety in his activity	low
interdependency	The agent's knowledge is quickly obsolete. The process-related knowledge has to be updated often.	high
	The agent's knowledge is relevant for a longer time if it is once established	low
process dynamic	The agent has major influence on the outcome of a process.	high
	The agent has minor influence on the final result of a process	low

Table 3.2. Attributes of complex processes. Process complexity of inspection activities is evaluated as suggested by Eppler [2].

3.5.2 Results

Data used to generate the profile was collected from inspectors and is shown in appendix A. Each process can be rated as Strong (1) in terms of knowledge intensity or Weak (0). The same with the process complexity which was characterized as High (1) or Low (0). In defense to this empirical study all processes were grouped to be at the same level although from the process mapping in the Department one may have the impression that some of them are at a higher level of detail than others. Inspectors participating in the survey added that in some cases answering with TRUE (strong, high) or FALSE (weak, low) was not always easy. Furthermore, a remark was made that some of the activities do vary in complexity and knowledge intensity depending on the type of facility inspected. For bulk facilities

(i.e. reprocessing plants, enrichment, fuel fabrication etc.) some of the processes may be more complex than for item facilities (i.e. reactors). Nevertheless, the results offer an overview of inspection processes and give a characterization for the study pointing out where the critical knowledge is or may be needed.

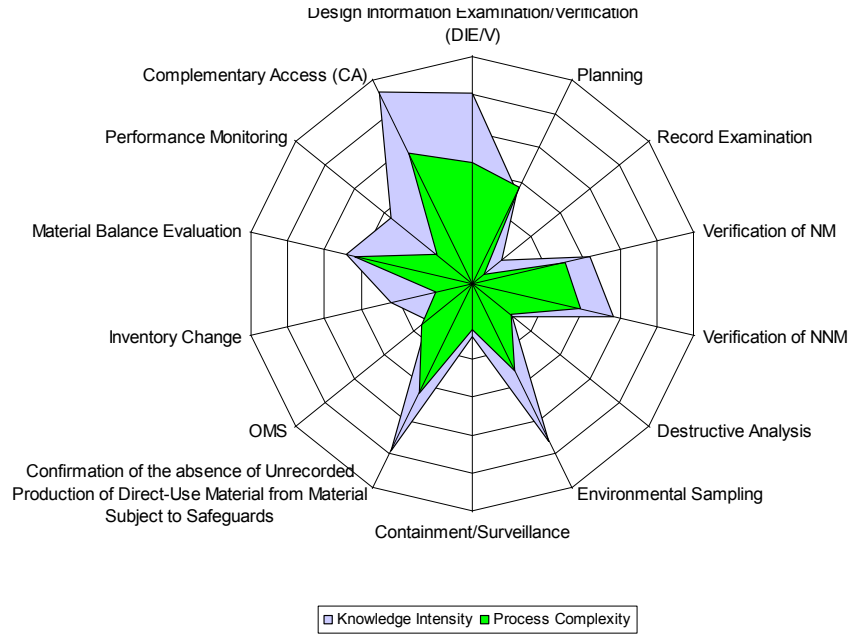


Figure 3.2. Knowledge Profile of Inspection activities based on Eppler's matrix combining the knowledge intensity of the process and complexity. The two activities that fall in the category Class 3 - are complex and knowledge intensive

In Figure 3.2 a profile of knowledge is depicted. Knowledge profile is a term adopted from work performed by [47] to show the *knowledge profile* of the human brain. Here, we refer to the profile of knowledge requirements needed in performing inspection activities. Based on the survey conducted it was discovered that Design Information Verification/Examination (DIV/E) and Complementary Access (CA) relative to other activities are considered to be the closest class 3 of the suggested classification. These processes are complex and are also knowledge intensive. The third activity MBE is also shown as a complex process which places it at the center of the matrix. The attributes that has mostly contributed the MBE being complex is the interdependency and number of agents involved. This can be explained by the fact that MBE evaluation is performed in coordination with a number of or-

ganizational units requiring more communication and coordination for inspectors. This activity is also knowledge intensive however less so in comparison to DIV and CA.

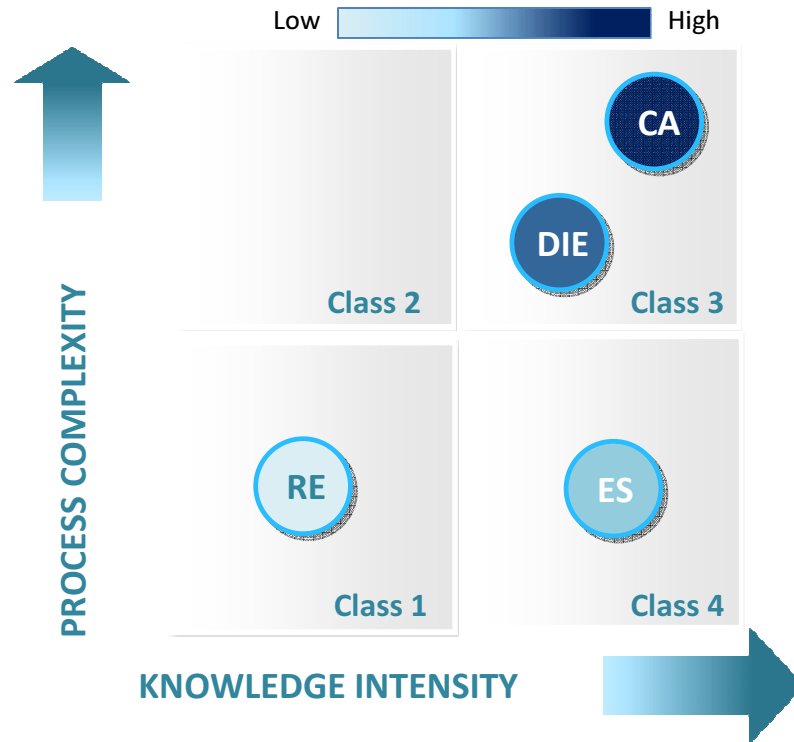


Figure 3.3. Classification of the Inspection Processes based on Eppler's Matrix

Another conclusion derived from the survey was that these processes, their complexity and knowledge intensity is dependent on the type of facility inspected. There are two broad categories of facilities: bulk handling facilities and item facilities. Process complexity seems to be higher for bulk handling facilities since usually these facility tend to be physically larger and involve more complex processes (e.g. Pu separation). The same is true for the knowledge intensity dimension which seems to be stronger in the case of bulk handling facilities. These results merely give priority the CA process and the DIE process for as best candidates for process-oriented knowledge management and use of models to explicate domain knowledge as means of designing processes. Next section looks at these activities and related concepts in further detail.

3.6 Conclusion

This chapter offered an overview of the complexity of the domain and offered in-depth looks at the nature of inspection processes. IAEA can be comfortably said that it represents a knowledge based organization. A great number of services provided by this organization is put under scrutiny of the international community. Verification activities represent a politically sensitive domain which requires convergence of knowledge resources across the organization as well integrating knowledge from outside sources. Knowledge of various nuclear processes combined with the ability of the inspectors to routinely collect data in the field is necessary for effective safeguards.

From the inspection processes studied it was discovered that most knowledge intensive activities which are also complex are the Design Information Verification/Examination and the Complementary Access which is slightly less complex but certainly knowledge intensive. It was established that these processes vary in their complexity and knowledge intensity based on the type of facility and obviously the size of the facility. Despite, it remains to be true that these processes requires attention by finding ways to optimize their execution making them as efficient as necessary and as much as possible knowledge driven.

By looking at various sources and intensities of knowledge present when dealing with DIV and CA processes, a concept comes across as central to the implementation of verification activities, evaluation and reporting there from. Both processes are measures that are applied under IS in order to generate the *SG Approach* which is the guiding metaphor in finding more effective and efficient ways of implementing Safeguards. Under Integrated Safeguards (IS) where optimal combination of measures is sought SG Approach becomes the crucial element in replacing the criteria based approach under traditional safeguards. The approach which is developed and evaluated also against the existing safeguards criteria entails not only processes which are knowledge intensive and complex (i.e. CA, DIV) but it also represents a platform where knowledge convergence can occur in achieving safeguards objectives all of this while combining concepts, activities and tools in support of information driven safeguards. This is true for both facility and state-level SG approaches. An SG approach is commonly prepared with information resulting from the DIV

design information examination and is strengthened with activities such as CA. It is therefore suggested that SG Approach can be the knowledge space that can be represented using a model-based approach organized through POKM. Hence, the next chapter will try to introduce a conceptual framework that represents SG related concepts with the use of modelling languages. The objective is to make concepts such as SG Approach explicit and manageable in a form of models applying a process view. Knowledge represented through modelling languages can be both interpreted by machines and used by inspectors.

Inspection Modelling: Conceptual Framework

4.1 Introduction

This chapter discusses the focus of the research performed. Applying models to describe the nuclear verification domain requires a modelling method that represents aspects of the verification system under study. Some of inspection related concepts were discussed in previous chapters and will be presented here in a integrated modelling framework abiding to the principles of the Open Models Initiative (OMI) and considering similar approaches such as the MDE and MDA [48, 7]. To this end inspection activities at a state level and facility are conceptualized through a number of meta-models defining modelling languages that allow for the creation of a model-based, adaptable, context-sensitive and objective-driven approach for safeguarding - Safeguards Approach for Facility X or State Y. A distinction needs to be made that the approach suggested here varies from commonly justified use of models to drive and configure systems development. The objective is not to use models solely in the context of software engineering i.e. by generating code out of UML models [49]. Models here are used under the scope of a modelling method to provide functionality such as:

- Automatically generate safeguards objectives for a state based on the state's physical model - focused on the completeness aspect of verification.

- Derive instances of inspection process models on facility, site or state level.
- Instantiate work plans for inspectors by assigning tasks to identified roles.
- Generating content in a form of descriptive or prescriptive models for documentation, analysis, simulation and evaluation.
- Offering an integrated modelling platform for creating knowledge-based process models, which represent externalized knowledge content and are managed through a POKM approach. i.e. PROMOTE and Process Oriented Knowledge Management (POKM)

In order to contribute to the performance and effectiveness of nuclear inspections engineering of methods and therefore use of models for conceptualizing inspection regimes represents means for creating a foundation of semantic content and structure that provisions a knowledge environment for inspectors to gain from the process knowledge and retaining the useful knowledge.

4.2 Modelling Framework

In order to introduce the modelling framework and its intended use we start by reviewing some of the underlying principles that support the use of models and modelling as an activity.

A *Model* in the Princeton dictionary is defined as the act of representing something. "A model is a formal specification of the function, structure and behavior of a system within a given context, and from a specific point of view (or reference point)" [50]. Definitions across different fields vary with meaning. For instance in mathematics a model has a different meaning compared to models used to represent an example or a sample of how something will/should look. One of the generic definitions accepted for this research is that of Whitten saying that models are used to "represent reality or vision" [32]. He stated this in the context of systems analysis and design methods. Open models initiative iterates that models are created with a purpose and represent a System under Study SuS [51]. According to Karagiannis et al, models *operationalize knowledge* and are classified as either being data, process or "knowledge" models [7]. Most of the definitions attempt to

dehumanize the use of models by associating them to representation of visions and idealized realities described with structures such as classes, objects [12]. The term model is generalized in every day use and can represent any of the views above. In this section a definition of models is offered specifically attributed to the system under study namely the nuclear verification and safeguards inspections. Models described hereof are instances of a meta-model that conceptualize the verification domain through modelling languages with semantic clarity based on the notation familiar to intended users. These models constitute a modelling technique, which in combination with a procedure as well as algorithms and mechanisms create an integrated modelling method for safeguards [7, 52].

The definition of *inspection models* used here is as a result of an activity broadly named as inspection modelling:

"Knowledge artifacts that facilitate through their analysis and evaluation understanding of inspection concepts and operationalize expert process knowledge otherwise lost with reference process models."

In addition to purpose, models can be also classified in terms of their use. Karagiannis and Woitsch claim that models can be considered as interpretable by either humans or machines. They may be understandable by both which is more difficult to achieve. Humanized models, which are understood and are interpreted by humans are referred to as *Knowledge Management Models* [12]. Such models may be partially corrupt whereas *Knowledge Engineering Models* are those that require a level of formalism and should be also processable by machines. This classification is based on the knowledge view of models where a representation of domain knowledge is merged with the formalism required for knowledge engineering [12]. Models provide an abstraction of physical systems that allow engineers to reason about systems [53]. Visual modelling according to [54] is on the rise not only for system engineering but also in the business domain.

The interest in models has been apparent in the industry and research amplified by Object Management Group's (OMG) initiative and followed by the investments in the industry [55, 56, 48]. Models, used for generating requirements, describing reality or vision, generating IT models and subsequently transforming them to source code are discussed in initiatives such as Open Models Initiative and the one

proposed by OMG, namely Model Driven Architecture/Engineering (MDA/E). In the case of OMG the focus is mainly on software engineering where models are viewed as the level of abstraction, an evolution from the object-oriented view. The Model Driven Architecture (MDA) promulgates a top down approach where platform-independent models document the business functionality and behavior of applications separate from the underlying technology. Instances of such models are created using a modelling language derived from the meta-meta model named *Meta Object Facility* (MOF) [48]. Through a chain of transformations enabled by tools now readily available from different vendors the aim is to establish a framework for creating first-class artifacts that can be stored, exchanged over the network and transformed from Platform Independent Models (PIM) to Platform Specific Models (PSM). There is another level of abstraction above PIM called Computation Independent Models. CIM, sometimes called domain model hides technical details representing more what the system is expected to do, therefore a computation independent view is captured with this layer [11]. The language of choice is the Unified Modeling Language (UML). CIM for instance includes modelling the business layer also with the use of UML. Domain models using languages such as UML to represent computationally independent views are challenged with the complexity of transforming such models to PSM models while ensuring the minimum semantic gap [57].

UML is the language that has been widely accepted as the industry standard in representing software engineering concepts from early requirements to detailed technical models. UML language models as suggested by MDA can be transformed from higher conceptual layers to more technical layers specifying implementation details. Further definition of MDA is given in [48] where it is envisaged that the technology will be available to also reverse code to models.

Another approach suggested by the OMI proposes similar benefits compared to the discussed proposal from OMG. Models, which can also be considered as artifacts are representations that are not only translated to source code but rather represent elements of situational method chunks which can build an information system [58].

There are other frameworks, which are seen in the context of enterprise information systems such as the one proposed by Zachman [59]. The framework named

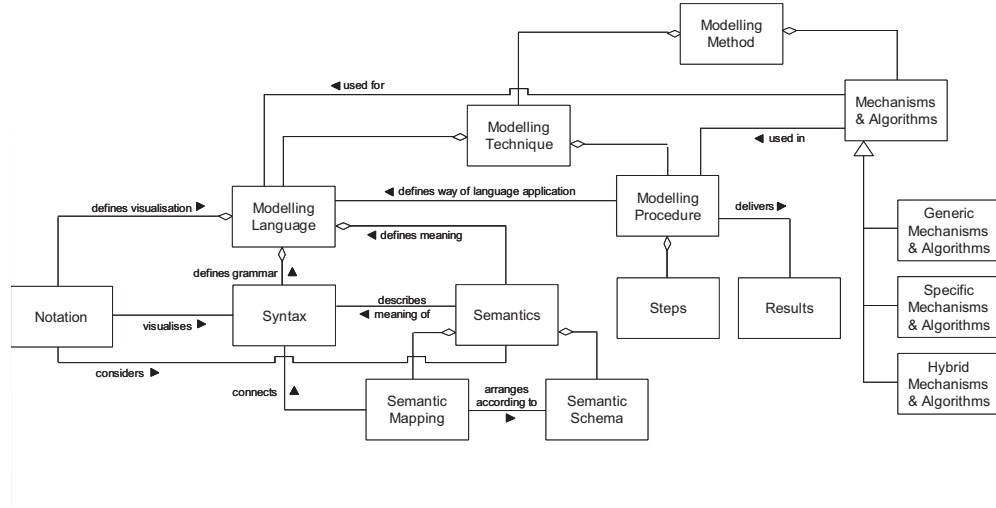


Figure 4.1. Modelling Method Elements introduced under the Open Models Initiative

with the author proposes a matrix of modelling artifacts that represent different views of an enterprise. This framework however differs from the OMG framework as discussed by Frankel in [60]. Next section looks at the Open Models Initiative (OMI) which possibly strikes the optimal balance of the two and focuses on a niche not considered by frameworks MDA and Zachman.

4.2.1 Open Models Initiative (OMI)

Although, nowhere explicitly stated in the feasibility study there seems to be a distinction in the purpose and application of models as proposed by OMI in contrast to MDA or even Zachman. It can be said that the modelling methods principle is closer to the purpose of situational problem solving methods - a functionality envisaged also for the inspection modelling method. Modelling methods as suggested in [7] are made up of a modelling technique, mechanisms and algorithms necessary to process models represented. This approach also supports the idea of models being transformed, integrated through mechanisms and algorithms to and with other types of models. Furthermore, it can support application of algorithms to evaluate models. Figure 4.1 shows the components of a modelling method. It does not have to be limited to generating code from models or reverse engineering models analogous to Model Driven Engineering (MDE). It suggests a meta-meta

model approach depicted in the figure where meta-models are engineered specific to a domain and may be used for representing data models in software engineering (e.g. ERD) or differently represent process models (e.g. BPM). This view of modelling and its application is the preferred one for the conceptual foundation introduced under the *Conceptual Nuclear Verification Framework*. A model is seen in the framework as a products of a method that consisting of a language or languages with a well defined notation, syntax and semantics. Any such modelling language is also followed by a procedure that outlines the steps for achieving the desired results. Such models can be formalised and processed by algorithms and mechanisms providing functionality to use and evaluate [7, 61]. In order to process models various formalisms may be used (i.e. graph theory, pattern theory, petri-nets etc.)

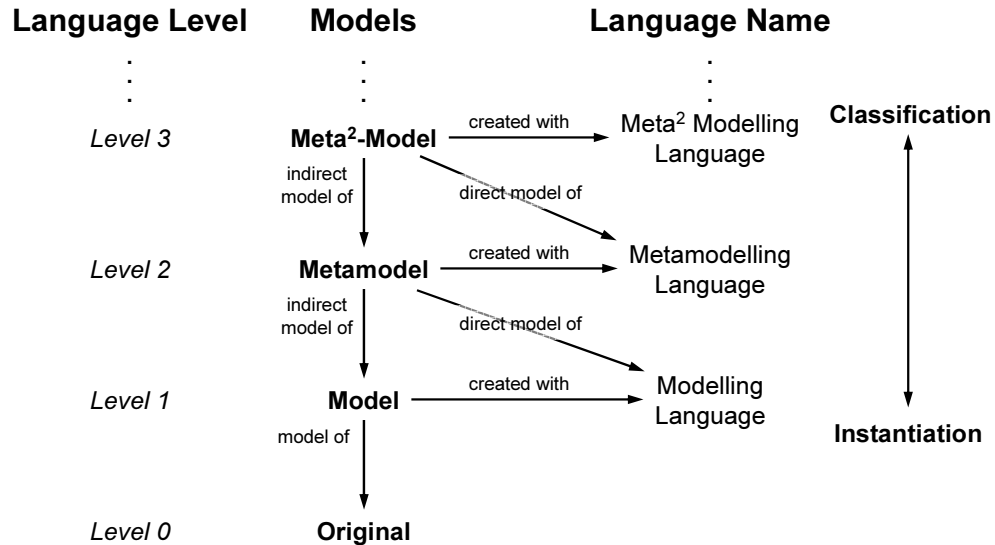


Figure 4.2. Model Integration Levels (Strahringer, Karagiannis)

The meta-model view in 4.1 shows the components of a method as introduced by the OMI. An example that can be used is the Business Process Modelling (BPM), a modelling technique with predefined modelling language notation (i.e. BPMN, EPC) syntax and semantics. Mechanism and algorithms may be used to evaluate such models. Examples of path analysis, simulation of cost, transport times can be formulated. In contrast to OMGs architecture where the focus is on

establishing a model driven approach for generating code through transformation this approach suggests modelling methods as a set of constructs for conceptualizing domains (mainly business domain) through the use of modelling language created with the necessary formalism for processing to also provision analysis, evaluation and simulation. Brinkkemper's claim that *"method engineering is the engineering discipline to design, construct and adapt methods, techniques and tools for the development of information systems"* had a motivational effect on this initiative and work from [61, 52, 7]. Based on research from Welke and Kumar, method engineering by Brinkkemper identifies three components: methods, techniques and tools [62]. Hence, a modelling method can be defined as *"an assembly of method fragments for a certain application scenario to achieve defined goals"* [63]. A modelling method as introduced in OMI represents the evolution of the method engineering concept where models are used to realize methods which can be assembled in a service for achieving desired results. Modelling is an activity for applying models or method fragments that can be combined or used as input to developing information system or offer functionality on its own. The purpose of the method engineering is not limited to generating code something more so with the OMG framework.

4.2.2 Metamodelling

Figure 4.2 shows the meta-model layers based on work from Strahringer adapted by Karagiannis [64, 61]. Starting from the meta meta-model each layer is considered as a modelling language created by the modelling language of the previous layer. It is not limited to 4 levels however it is believed that going beyond level 3 might not be necessary. This does not contradict also the modelling framework of OMG where layers are described from M0 to M3.

Meta-models are models used to create a modelling language. According to the meta-model the syntax of a language is also defined in contrast to approaches such as graph grammar [7]. A meta-model defines all the language constructs providing basis for a formalism in the models created. In some cases meta-models are not sufficient for expressing all syntactical rules for creating a valid model therefore such rules can be expressed with additional formalism such as the Object

Constraint Language (OCL).

The proposed framework is based on the principle of method engineering where a modelling technique and mechanisms are used to streamline activities and tools for analyzing and evaluating a certain verification problems. Inspectors for instance would be able to model the State inspected using modelling languages based on integrated meta-models. Algorithms can be used in evaluating an approach for safeguarding a State. This representation will allow for structured analysis of the weapons acquisition path and risk based definition of objectives to be met in verifying a state. Next chapter will provide an additional level of formalism which can be used in formally representing modelling languages for application of algorithms and mechanisms. The application of pattern theory will be introduced which contains graphical and mathematical formalism sufficient to represent conceptualizations of the physical model - state's nuclear programme. Furthermore, this level of formalism can enable applications such as automatic generation of state level safeguards objectives and related inspection processes by linking means objectives to activities of the process. Constructs of pattern theory or *generators* can be used to also support the transformation of verification concepts represented with high level inspection modelling languages to data and process structures. Such a formalism can support transformation and mapping of computationally independent models to technical models in UML.

4.3 A Nuclear Verification Conceptual Framework

The conceptual nuclear verification framework is made out of building blocks that conceive a new modelling method referred to according to purpose as the *integrated Safeguards Modelling Method (iSMM)*. This method is based on different facets focused on modelling aspects of Technology and Knowledge Management in addition to the operational perspective termed Safeguards covering elements specific to the nuclear verification. For the KM aspect the *PROMOTE* approach and its modelling language was chosen whereas for representing the technology aspects, standard models based on UML can be used. The purpose of PROMOTE is to

provision for inspectors process oriented knowledge management whereas technology modelling refers to more technical models that will represent the technology in support of the operational and KM processes. Modelling languages here can represent information technologies or other used by inspectors in the field. The framework offers a comprehensive view of three aspects considered important for verification method engineering with emphasis on knowledge management and the enabling technology. All three perspectives have to exist in order to ensure the needed preservation of inspection procedural knowledge for a structured and information driven safeguards.

Such a framework represents a high level structure that serves as foundation for creating the modelling method based on the concepts introduced in previous chapters and in [7, 61]. Modelling methods provide a theoretical basis for enabling modelling activities by introducing major components such as modelling languages, modelling procedures, mechanisms and algorithms that can be applied onto models. Such models correspond to a meta-model that defines the syntactical elements of the used modelling languages. Introducing a proper set of interconnected modelling languages to support the three perspectives *safeguards*, *knowledge management*, and *technology* of the conceptual framework is the work at hand. Before deeper insights to the modelling method the above mentioned perspectives are introduced in more detail.

Figure 4.3 depicts the three perspectives of the framework. The operational perspective consists of five components: technical, strategic, legal, analytical and on-site activity. It covers aspects specifically related to the safeguards system. Most of the components do not need further clarification whereas the word "technical" may be ambiguous since it is the term used to refer to equipment and instruments placed at facilities. Such equipment is used for performing measurements, which is an important part of inspection. Another component that may require explanation is the "analytical" component that stipulates analytical services for samples taken at nuclear facilities. To offer a complete overview of all operational aspects of safeguards all these components have to be "en suite" in a framework with the right combination of modelling languages. The figure also shows the knowledge management perspective, which covers aspects focused on facilitating knowledge products in support of safeguards. Technology perspective

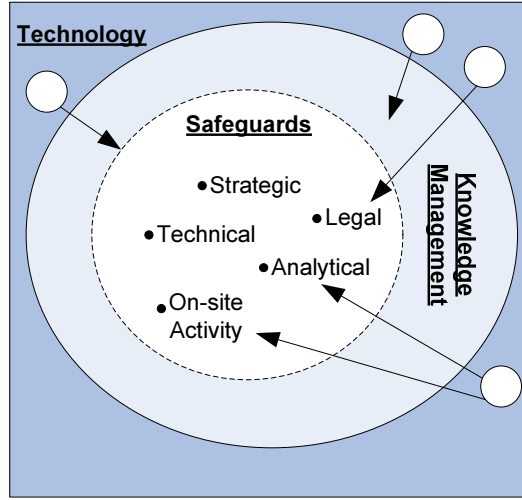


Figure 4.3. Elements of the conceptual framework for nuclear verification. It consists of three perspectives safeguards, knowledge management and technology. The operational perspective consists of 5 sub-components.

depicted as the environment around the operational and knowledge management perspective. It mostly refers to information technology that makes services accessible in support of data acquisition, processing, execution and evaluation of models. Furthermore, it covers aspects related to the technical issues of the operational perspective.

Safeguards Perspective: This is represented by modelling languages that document the operational elements of nuclear inspections. Inspection procedures, strategic and technical objectives, legal requirements and analytical processes used to reach conclusions are incorporated here. Nuclear processes and the nuclear fuel cycle are also represented in this view since they serve as specifications for conceiving inspection processes. Reference models of facilities within a state and the related safeguards objectives for each state/site/facility are modelled in order to contextualize actual objective-driven inspection processes.

Knowledge Management Perspective: Based on process-oriented knowledge management [8], here the so called knowledge management processes are modelled describing the tasks for creating, storing and disseminating inspection knowledge. The same way inspection processes are derived from the nuclear processes,

knowledge perspective includes languages that help describe knowledge processes relevant to the inspection process. Additionally, languages represented under this perspective are used to map knowledge resources, represent knowledge structures in order to identify knowledge necessary - "what is known" and "what needs to be known" in supporting inspection processes. Skill Models, Knowledge Map Model in combination with models from the safeguards perspective are used to establish Process Oriented Knowledge Management (POKM) .

Technology Perspective: It includes modelling languages to represent the technology layer. Languages here are used for instance to describe the IT Architecture or more technical ones representing orchestration of services provisioned by SOA. Languages such as OWL-S, OWL-WS and UML can be used to represent this perspective. Another interesting outlook of this perspective is the growing trend to perform inspections through remote monitoring therefore modelling these technical aspects will improve the alignment of such technology to organizational processes and objectives. In remote monitoring data such as containment and surveillance in addition to unattended safeguards is made available for review at the IAEA headquarters. Such an approach would require an enterprise architecture where remote monitoring services are also modelled part of the IT architecture. Considering that safeguards largely depends on the application of equipment (i.e. Non Destructive Assay NDA) this perspective is therefore broadly named as "technology" not to exclude representation of other technologies in addition to information, communication.

4.4 integrated Safeguards Modelling Method (iSMM)

In order to support the three different views introduced in the previous section with models a set of modelling languages relevant to the nuclear inspection domain are defined. Although each of the modelling languages presented are from a conceptual viewpoint independently defined, connections between these languages are supported through inter-model relationships highlighting the coherence on the model level. Thereby, the goal of modelling with iSMM is to externalize knowledge:

- about the processes applied at the facilities/states throughout all phases of the nuclear fuel cycle

- about verification approaches at the Facility, Site or State
- about verification objectives on the Facility, Site or State level
- on optimal processes required by the IAEA to perform the nuclear inspections at facilities/states
- about KM activities in support of inspection processes and
- about technology supporting inspection and KM processes

Process-oriented models such as the nuclear fuel cycle model and the inspection process model can be used to document and create a "protocol" or an approach applied by the IAEA in order to ensure that nuclear activities in states are accordingly inspected and comply with the undersigned safeguards agreement. The Agency's authority to apply safeguards stems from its Statute - "pursuant to this authority, the Agency concludes agreements with States, and with regional inspectorates, for the application of safeguards" [18].

This method will also require mechanisms and algorithms that will ensure that inspection models are checked for their completeness and correctness. The technique involving modelling languages for representing formally inspection concepts and procedures is generally referred to as *Inspection Modelling*. The integrated safeguards and related concepts are explained in Chapter 3.

As depicted in 4.4 the operational perspective is viewed as the layer of "business" [8] representing inspections at facilities. In a sense an attempt is made to "reconstruct" or map activities performed by the facilities/states in order to verify them. Common reference models for each type of facility are available and can be re-used for representing a facility/site or state (a kind of a template or a virtual state file). A top-down and structured procedure is applied to represent verification objectives derived from the top layer (nuclear activities i.e. physical model) leading to the definition of the inspection processes. Because the nuclear processes and inspection processes are represented at a different abstraction level, inspection objectives as used to link the two. The functionality of transforming physical models into inspection objectives can be also achieved automatically with the use of algorithms discussed in the next chapter. The nuclear processes mapped define the context for designing inspection processes which currently exist in the organization

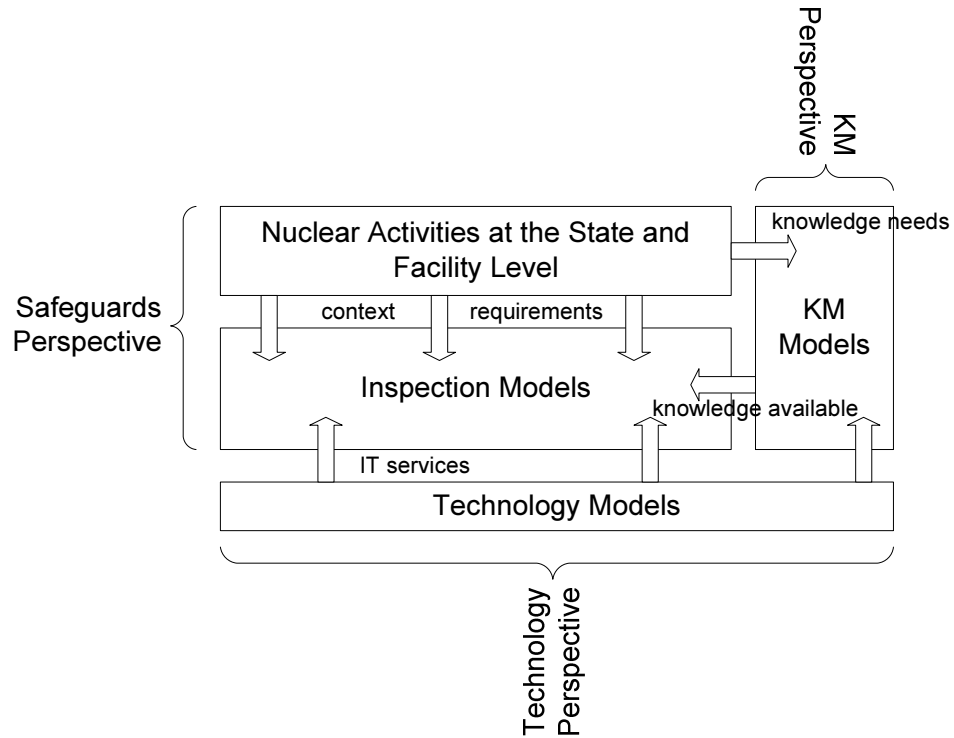


Figure 4.4. Conceptual framework and high-level requirements for the *integrated Safeguards Modelling Method (iSMM)*.

only as reference processes. The layer broadly named as *Inspection Process Models* actually contains of models related to the implementation of nuclear inspections for specific facilities/sites/states it can be considered an *inspection work plan* (tasks, objectives, resources etc.). On the other hand the KM models layer describes and identifies available KM activities, roles, skills and resources that are needed to actually perform inspection duties. KM models are also created to inter-reference all levels of inspection models and nuclear process models . Moreover, such models can serve as valuable content that makes creating valuable content for describing verification strategies in a states but also managing the related inspection knowledge. It can also be seen as a console that steers the use of knowledge products and driving the inspection processes.

The layer consisting of technology models provides means to represent the technology for implementing integrated safeguards through existing information systems. In addition to identifying the technology supporting the safeguards as-

pect the objective is to model technical details that are generated by transforming higher level modelling abstractions in support of process execution (i.e. through workflows) or even source code generation [8, 48]. Due to a large and heterogeneous technologies available for supporting inspections this layer can also serve the integration layer for information and other technologies at the inspection process level [16]. These models are integrated by reference to models of the knowledge management layer [12]. This integration will also help reduce the semantic loss between the inspection processes and the IT and technical services available [57].

4.4.1 Operational Meta-Models

Based on the requirements outlined for the modelling method (iSMM), modelling languages support the operational perspective by capturing (a) strategic issues in terms of objectives of the participating parties (e.g. IAEA inspectors, member states), (b) description of nuclear facility/site organizations and relationships between these facilities/sites, (c) inspection processes applied for nuclear inspection activities, (d) nuclear knowledge within the IAEA and knowledge about processes involved in a potential weapons acquisition, and (e) organizational issues of the IAEA relevant for execution of nuclear inspections. To meet the requirements of representing all relevant views existing language are used through their extension or new languages are defined from scratch to suitably represent the System under Study (SuS). Excerpts of meta-models and relationships between these meta-models are shown in 4.5 where the core elements from a syntactical point of view are introduced. In the forthcoming section a comprehensive description for each meta-model is provided. These descriptions provide a link between the aspects of nuclear inspection represented and the modelling language used to represent these. The meta-models shown here represent the SG perspective of the overall framework.

4.4.1.1 Nuclear Fuel Cycle Model

The Nuclear Fuel Cycle Model (NFCM) is meant to describe the planned or ongoing nuclear activities in a state. It identifies all known and declared nuclear processes, which serve as basis for deriving the corresponding inspection activities.

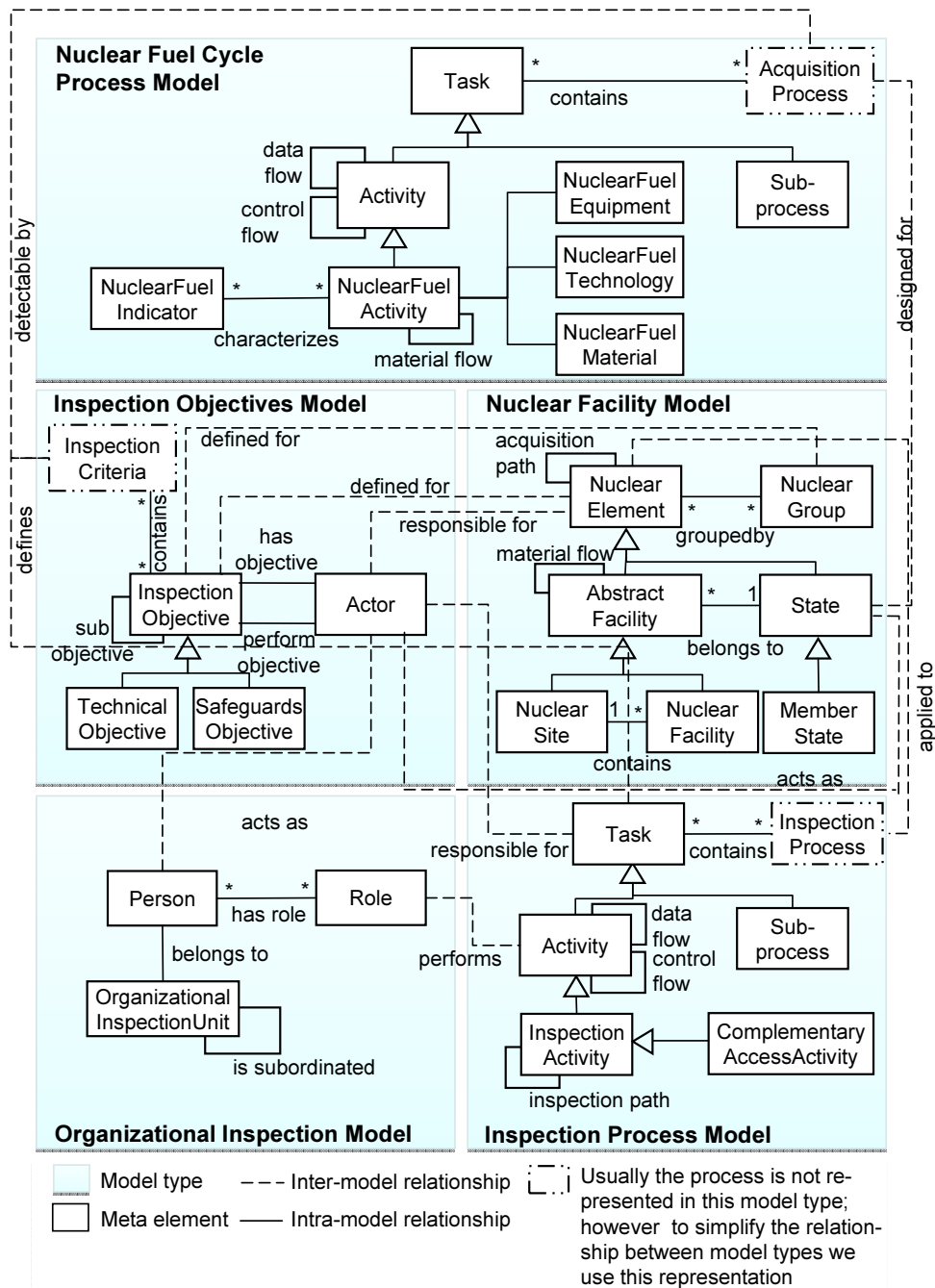


Figure 4.5. Syntactical elements of the inspection model types relevant for the *Safeguards Perspective*

In addition to representing the fuel cycle in a state it can be used to identify, describe and characterize every known process for carrying out each step necessary for the acquisition of weapons-usable material. It can be used to represent all plausible acquisition paths for highly enriched uranium (HEU) and separated plutonium (Pu) as well as the associated equipment, material, technologies that characterize such processes. Specific attributes known as Indicators associated to nuclear processes and are evaluated in the context of the activities declared by the state (cf. designed for relationship). NFCM models and associated models of facilities provide context for generating verification objectives, which are met by inspection processes.

4.4.1.2 Nuclear Facility Model

This type of model describes a nuclear Facility. Based on the design information received from the state and the information collected through verification activities Nuclear Facility Model (NFM) represents all aspects of a facility and its function. It includes a conceptualization of how facilities are structurally organized in terms of nuclear material accountancy. Each facility consists of at least one material balance area (MBA) for nuclear material accountancy purposes; selection of those strategic points which are key measurement points (KMPs) for use in determining nuclear material flows and inventories. Model based representation of facilities provides reference for nuclear material accountancy and the verification activities that need to be implemented to ensure a permanent continuity of knowledge for the material received, processed and shipped to other facilities. The model can be used to represent one facility or a group of facilities based on a common location referred to as *site*. For complementary access purposes this model can be used also to describe any other type of location. Material flow between modelled facilities can be used to represent their relationship. Such relationships can exist between facilities within the same state or internationally.

4.4.1.3 Inspection Objectives Model

Based on the safeguards agreement with the state and the nuclear fuel cycle in the state high level strategic safeguards objectives need to be defined. Once the

state level or facility level objectives are defined lower level technical objectives are also depicted. Modelling strategic objectives can be done using a goals model here named as *Inspection Objectives Model*. Objectives model will show the hierarchy of objectives decomposed through the means objectives that represent the safeguards criteria for inspecting facilities, sites or states based on the risks identified. Objectives are linked to means-objectives that represent methods to achieve these. The lowest level of means objectives in the hierarchy relates to processes and inspection activities modelled using the inspection process model.

4.4.1.4 Inspection Process Model

Inspection Process Model represents a business process model extended for inspection activities and inspection pathways. Here random inspection activities as well as complementary access activities are incorporated. Complementary Access (CA) can be performed with a 2 hours or 24 hours advanced notice [45]. Details about CA as an inspection activity are provided in Chapter 3. Inspection implementation activities based on the criteria and objectives can be graphed using inspection process models. They can be used also to externalize expert know-how and serve as an entry point to knowledge management models. It is the intention to create inspection process models that can represent: *knowledge content and are an entry point to knowledge products represented with PROMOTE*. Processes and activities representing SG aspect based on safeguards objectives create an *inspection path* which is not only knowledge driven but also aligned to the organizational goals and objectives. Guided creation of inspection pathways tailored for the specific state and nuclear activity will help implement integrated safeguards approach in many of the states still under traditional safeguards. Such an approach is founded on the principles of effective but also efficient inspection processes. Its conceptualization and representation with a model based and knowledge aware method extends benefits by introducing adaptability to changes by preserving procedural verification knowledge.

4.4.1.5 Organizational Inspection Model

The organizational aspect for actually executing inspection processes is expressed using the *Organizational Inspection Model*. Roles and staff involved in performing inspection activities are represented with this model. It covers organizational aspects while establishing a link to inspection objectives and the modelled skills represented with PROMOTE models. Furthermore, it can represent roles pertaining to the activity of inspection modelling. At the IAEA for nuclear inspections it can consist of a process designer that is in charge of designing optimal inspection processes in accordance with safeguards agreements and other legal aspects. While senior inspectors are responsible for devising safeguards approaches other inspectors can use inspection process models as content or process stepper [65] for planning, preparing or training in general. The idea is to realize this in a so called *Inspection Knowledge Room* where inspectors are familiarized with knowledge made explicit through models. This model can also help organize security roles and subsequently role based use of the modelling method.

4.4.2 Safeguards Perspective Applications

All of the above modelling languages described are a part of an inspection modelling method iSMM. The inspection modelling represents a technique that uses modelling languages integrated at the meta-model level. The meta-model approach here provisions for integration and syntactical correctness of the modelling languages. Any constraints that can not be covered with the meta-model can be formalised also with Object Constraint Language (OCL). This level of formalism allows for instances of the meta-model to be processable using algorithms and mechanisms. The level of formalism can be used to verify the correctness and completeness of modelled state activities. Furthermore, with the necessary formalism of the language an example application scenario would be to automatically or semi-automatically generate safeguards objectives. Modelling *objectives* and *means* to achieve these objectives can be used to generate knowledge-based processes representing inspection activities for a State-Level Safeguards Approach (SLSA) then customized and tuned for a particular state. Inspection activities are subsequently derived from the identified safeguards objectives and are put in use for inspection

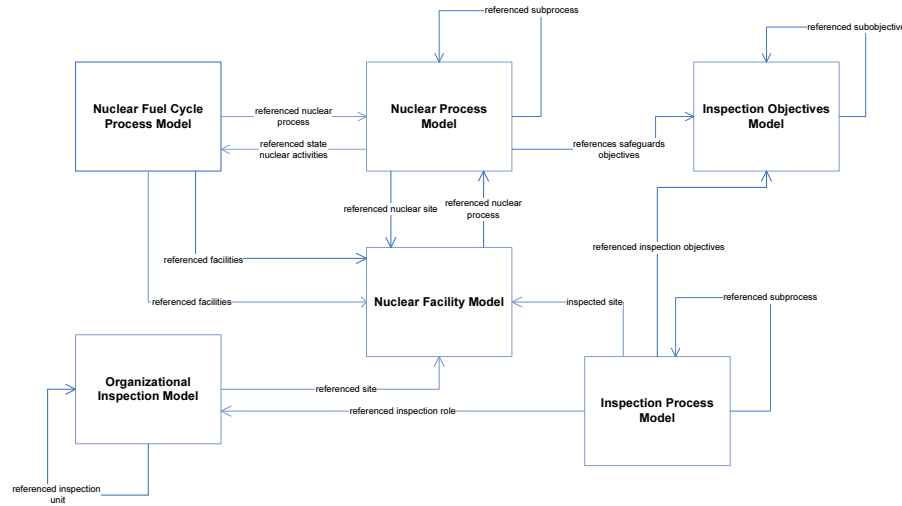


Figure 4.6. Meta-model of interreferenced inspection models representing the operational perspective of the conceptual framework

by instantiating plans referred to as inspection pathways (or simply work plans). Figure 4.6 represents the inter-referenced inspection models that define the SG perspective of the framework. It can be assumed that similar inter-reference exists with the meta-models of PROMOTE languages and technology languages such as UML.

4.4.3 The Meta-Meta Model View

Applying the theoretical foundation provided under modelling methods as introduced with open models and partially also under MOF, the conceptual framework can be presented as shown in Figure 4.7. The three meta-models: Safeguards or inspection meta-model (SG perspective), KM meta-model (PROMOTE) and the technology meta-model (e.g. UML) are shown side by side. The three are meta-models or a collection of meta-models, which can also represent a separate modelling methods. They are integrated at either the meta-meta-model, meta-model or even the model level; M0 in MOF L0 in Strahringer and Karagiannis [64, 61]. The SG perspective is represented with the inspection models whereas PROMOTE and UML meta-models will be integrated to support the SG perspective of nuclear verification. This hybrid of methods or languages represents an

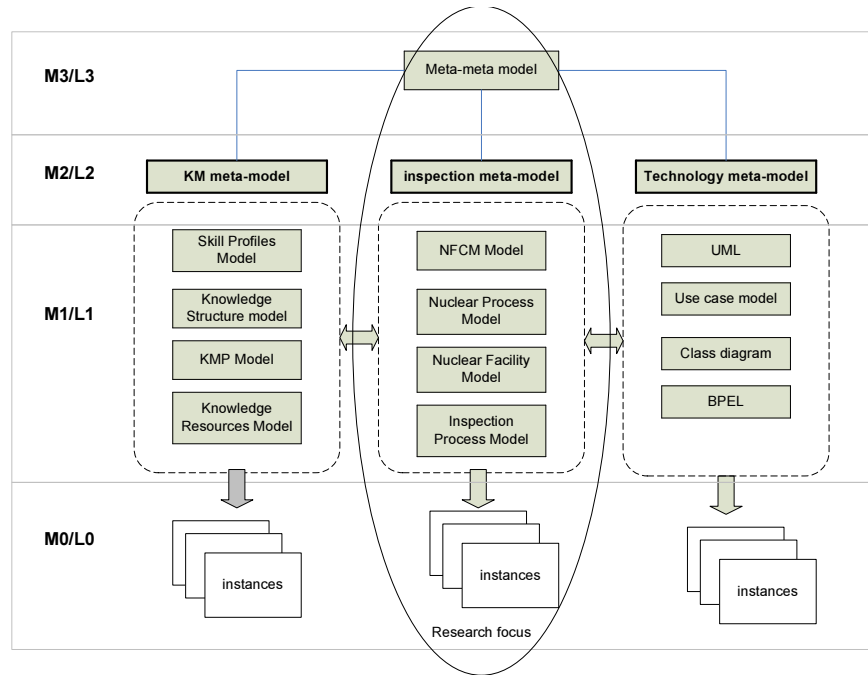


Figure 4.7. A structured view of the conceptual nuclear verification framework consisting of the core inspection meta-model with models representing the SG perspective and the KM and Technology meta-models which represent the perspectives in support of SG. The focus as shown in the figure is on inspection meta-model

approach to combine "best-of-breed" where knowledge management languages and technology languages in a model-driven approach support the nuclear verification domain and its core processes.

4.4.4 Modelling Procedure

Figure 4.8 shows the three building blocks of an integrated modelling method iSMM representing the three perspectives of the conceptual framework discussed above. The Operational Perspective which consists of modelling languages derived from the inspection meta-model are surrounded by the KM meta-model (PROMOTE) and the technology meta-model. There should also be a procedural aspect represented as a life-cycle for the inspection modelling method where high-level steps are:

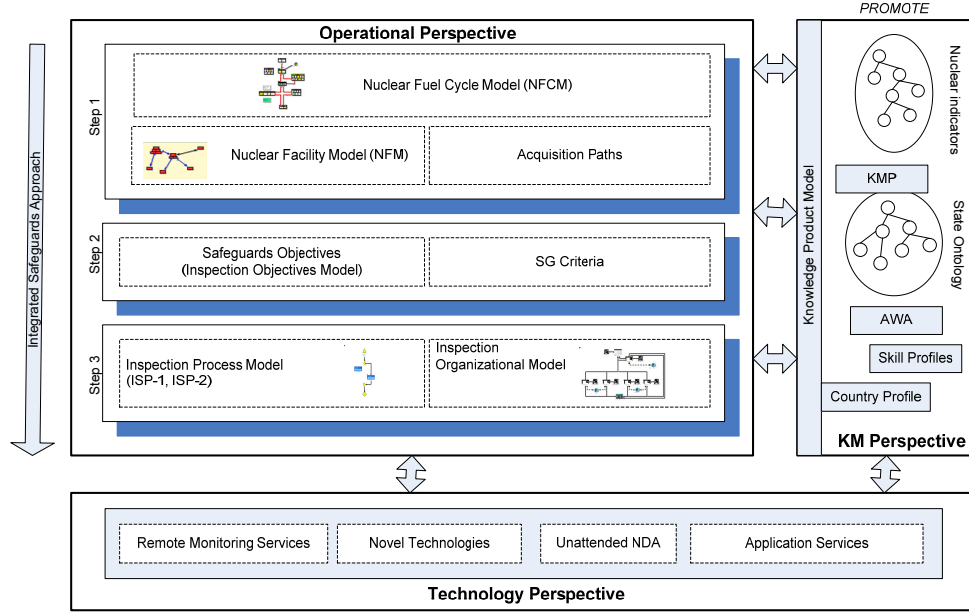


Figure 4.8. Building Blocks of the integrated Safeguards Modelling Method. Step-wise procedure for creating a Safeguards Approach.

1. Modelling the physical model and the state declared activities,
2. Modelling the SG Objectives and SG Criteria (algorithms are applied to derive the objectives check their completeness against acquisitions paths).
3. Modelling inspection processes aligned to the derived SG objectives (means of achieving the objectives). Also different organizational aspects are modelled to instantiate the inspection processes into usable work plans.
4. Modelling the knowledge in the organization and navigating through inspection processes that serve as an entry point.
5. Modelling technology aspects that support the inspection processes.

The next section will be looking at all the modelling languages representing modelling techniques of the iSMM. In addition to the syntactical elements shown in Figure 4.5 languages will be depicted showing their notation and semantics.

4.5 Modelling Languages

Language represents a notation of thought [66]. A modelling language is a language used to express the statements in models of some class of SuS. This section will depict the inspection modelling languages. In addition to syntactical elements and notation an attempt will be made to show the origins of the modelling primitives citing safeguards concepts and graphical representations already in use in the inspectorate. The objective is to introduce modelling primitives that are closely related in some cases visually identical to those used by inspectors and other experts in the department of safeguards.

There is sufficient justification why modelling in general and process modelling specifically are favoured by any modern organization. Some of the aspects are discussed in previous sections. One being that through models knowledge can be operationalized [7]. Modelling represents a learning process and helps document understanding of the people involved [67].

Before defining the inspection modelling languages an overview of guidelines for designing modelling languages is provided based on available literature. There have been efforts in literature to present guidelines or rules for designing modelling languages summarized next [68, 65]. Note has to be made that in some cases there is an apparent overlap between the guidelines.

4.5.1 Modelling Guidelines

Correctness Principle (language adequacy) also referred to as language adequacy in the newly introduced principles by Schuette covers requirements for syntactical and semantic correctness [69]. Considering syntactical correctness means that the modelling elements are defined using an approach such as meta-modelling or graph grammar [7, 70]. The former provides for correctness of modelling languages by formalizing constructs based on a meta-model or model of the models. Graph grammars is based on graph theory a formalism necessary in ensuring that the modelling language is correct from a syntax point of view. On the other hand the model must also be semantically correct. This can be established by ensuring that each language element is unique and unambiguous allowing domain experts to express statements that are not only correct syntactically but also their meaning

communicates clearly their purpose [68, 7]

Relevance (construction adequacy) This aspect considers whether or not all elements of the model and relationships are relevant to the system under study. Secondly, determining whether all elements can be validated and all fit the purpose of the model. This could be determined by considering if the model itself contains less information than otherwise. This is also described in literature as the minimalistic approach when dealing with data models [71]. The character of the model, which can be too specific or too general, is related to the view of relevance.

Very general reference models tend to be too general. Examples of possible criteria for determining relevance can be [65]:

- Models that represent a benefit to the clients
- Organizational models which are thought to hold a potential through reorganization bringing improvements/savings
- Models representing processes that have many interfaces and serve transparency (pertains to process models)

A rule of thumb is "as much information as necessary, as little information as possible" [65]. Also, when it comes to appearance it depends on the objective models are intended to fulfill therefore the objective should be set clearly beforehand.

Economic Feasibility Rule models have to be feasible based on two properties: robustness and adaptability. This guideline sets an upper-bound on the modelling efforts. Customers that apply models are responsible for monitoring their costs and benefits. This principle is analogous to all types of solutions where the benefits of using a model need to exceed the costs associated with it (i.e. complicated to model, takes too long etc.)

Rule of Clarity Models are useful if clear to the reader, third party. This is in particular important for determining if the correctness requirements are fulfilled. Sometimes the syntactical correctness and the presentability/appearance of models are in conflict. Under this rule generally one has to consider the aesthetics, structure and the intuitive acceptability or how understandable it is.

Rule of Comparability - here we speak about two types of comparability semantic and syntactic. The later can be achieved through a meta-model approach

where elements of one meta model can be compared with the elements of the other modelling language. When dealing with semantics the use of uniform symbols and notation can help streamline semantic comparability.

Systematic Structure this is an important rule when dealing with layers of modelling where for example upstream models become too complex and therefore need to be followed by downstream models. Having processes models followed by subprocess models should be complete describing the complete process leaving no gaps. Integration of individual views needs to be considered. This is the case also with other models such as inspection objectives model that represents a decomposition of objectives that need to always point to a root objective (highest level objective). The level to which models need to be followed by downstream models is not specified. According to Davis [72] referring to the process models, the informally expressed golden rule for decomposition is "if it looks sensible it probably is sensible if it looks silly it probably is silly."

The so called new guidelines presented by Schuette extend this model in a model called *Guidelines of Modelling* (GoM) where the correctness rule was redefined under language adequacy further discussing the formalism necessary for a model so that it can also be processed. This extends the former correctness and relevance rules. The construction adequacy is also related to the former rule of relevance where it is said that the modelling has to be tied to the purpose it serves for the modeller and the intended user. A more problem solving orientation is given to the purpose of modelling.

4.5.2 Representational analysis

Another practice known under the name *representational analysis* can serve as basis in evaluating modelling languages. It is defined as completeness or the extent to which the modelling grammar has a deficit of constructs that map to the set of representation theory. The the so called ontological clarity deals with the extent modelling grammar constructs are overloaded, redundant and excessive [73]. Bunge-Wand-Webber (BWW) may be a good starting point to study the representational capabilities of conceptual modelling languages. Bunge ontology extended by Wand and Weber consecutively in 1993 and 1995 contains a set of real world

constructs against which Weber suggests analysing the representational capability of modelling techniques [74]. This is done in terms of completeness and clarity.

4.6 Inspection Modelling Languages

This section describes the modelling languages and presents their notation, semantics and syntax. The languages are based on symbols, practices already existing at the department so to bring familiarity and common understanding between the modellers and users of the model. Languages presented make up the operational perspective and represent a component of the iSMM.

4.6.1 Nuclear Fuel Cycle Modelling

This language enables high-level representation providing an overview of nuclear activities in a state. Such a model has the objectives of representing the nuclear fuel cycle by identifying every known nuclear process in a country characterizing its nuclear programme. It is based on the official declaration provided to the IAEA - and can be supported using information from Open Source. The modelling constructs represent nuclear activities such as reprocessing, enrichment, reactors or fuel fabrication. It is a modelling language to represent the nuclear process by identifying activities their relation and the nuclear material flow from one activity to the other. Nuclear fuel cycle is defined as "a system of nuclear installations and activities interconnected by streams of nuclear material." [30]. The nuclear fuel cycle can be closed or open therefore the modelling language must allow representing both. An example of a closed cycle would be spent fuel received from reactors which is fed to a reprocessing activity that might feed back nuclear material to the fuel fabrication activity and eventually end up as fresh fuel used again in a reactor. This represents a closed cycle.

The next section will describe the notation used which is based on an IAEA internal paper where notation was specified for describing the physical model of a state [1]. The notation visualizes the activity and the technology used for performing that activity. The status of the activity and corresponding technology can be attributed as *none* implying it does not exist in the subject country. Furthermore

Element	Notation	Semantics															
Mining and Milling	<table><tr><td colspan="2">MINING & MILLING</td></tr><tr><td>U</td><td>Th</td></tr></table>	MINING & MILLING		U	Th	Is a reference to the activity of Mining and Milling which entails taking Uranium (U) or Thorium (Th) and preparing for fuel conversion.											
MINING & MILLING																	
U	Th																
Conversion	<table><tr><td colspan="2">CONVERSION</td></tr><tr><td>CONV.1</td><td>CONV.2</td></tr></table>	CONVERSION		CONV.1	CONV.2	Conversion activity. It covers pre-conversion (CONV.1) and post conversion (CONV.2)											
CONVERSION																	
CONV.1	CONV.2																
Fuel Fabrication	<table><tr><td colspan="4">FUEL FABRICATION</td></tr><tr><td>U met</td><td>UO₂</td><td>MOX</td><td>Exp.</td></tr></table>	FUEL FABRICATION				U met	UO ₂	MOX	Exp.	Fuel Fabrication which is characterized with the activity of fabricating fuel to be used in Reactors. It received nuclear material from the conversion activity.							
FUEL FABRICATION																	
U met	UO ₂	MOX	Exp.														
Enrichment	<table><tr><td colspan="5">ENRICHMENT</td></tr><tr><td>GAS CENT.</td><td>GAS DIFF.</td><td>AERO</td><td>MLIS</td><td>EMIS</td></tr><tr><td>CHEMEX</td><td>IONEX</td><td>AVLIS</td><td>PLASMA</td><td></td></tr></table>	ENRICHMENT					GAS CENT.	GAS DIFF.	AERO	MLIS	EMIS	CHEMEX	IONEX	AVLIS	PLASMA		Enrichment as one the sensitive activates of nuclear fuel cycle. Low enriched uranium can be enriched by increasing the abundance of the isotope 235 into HEU uranium
ENRICHMENT																	
GAS CENT.	GAS DIFF.	AERO	MLIS	EMIS													
CHEMEX	IONEX	AVLIS	PLASMA														
Reactors	<table><tr><td colspan="4">POWER REACTORS</td></tr><tr><td>GCR</td><td>AGR</td><td>HTGR</td><td>LWGR</td></tr><tr><td>LWR</td><td>HWR</td><td>FAST</td><td></td></tr></table>	POWER REACTORS				GCR	AGR	HTGR	LWGR	LWR	HWR	FAST		Power Reactors used for generating power			
POWER REACTORS																	
GCR	AGR	HTGR	LWGR														
LWR	HWR	FAST															
Research Reactors & Critical Assemblies	<table><tr><td colspan="4">Research Reactors & Critical Assemblies</td></tr><tr><td>Research</td><td>C.A.</td><td>Pu Production</td><td>NAVAL</td></tr></table>	Research Reactors & Critical Assemblies				Research	C.A.	Pu Production	NAVAL	Research Reactors and Critical Assemblies							
Research Reactors & Critical Assemblies																	
Research	C.A.	Pu Production	NAVAL														

Table 4.1. Elements of the Nuclear Fuel Cycle Model used to describe the *front end* activities of the nuclear fuel cycle.

the scale the activity and related technology is developed can be characterized as *production* or *research only* scale. Each status in the respective order is visually represented with colours *white*, *green* and *yellow*. Tables 4.1, 4.2, 4.3 show the notation and each element of this modelling language and brief description is provided. Examples of models shown in Figure 4.11 show technologies related to the particular activity with one of the three colours described. For example in the same figure Ruritania is depicted to have fuel fabrication at production scale shown in green. Table 4.3 shows also the relations between nuclear activities which can represent material flow. There is also an association relation which can be used to relate activities which do not necessarily have material flowing from one to the other.

The modelling language *Nuclear Fuel Cycle Model* can be used for two complementary but distinct purposes:

Element	Notation	Semantics
Reprocessing	REPROCESSING NON AQUEOUS AQUEOUS	Is a reference to the activity of Mining and Milling which entails taking Uranium (U) or Thorium (Th) and preparing for fuel conversion.
Heavy Water Production	HEAVY WATER PRODUCTION	Production of Deuterium known as Heavy Water.
Spent Fuel Storage	SPENT FUEL STORAGE	Fuel Fabrication which is characterized with the activity of fabricating fuel to be used in Reactors. It received nuclear material from the conversion activity.

Table 4.2. Elements of the Nuclear Fuel Cycle Model used to describe the *back end* activities of the nuclear fuel cycle

Relation Element	Notation	Semantics
Nuclear Material Flow	CONVERSION CONV.1 CONV.2 → LEU FUEL FABRICATION U met UO₂ MOX Exp.	Modelling relation element N-Material Flow representing the flow of nuclear material (e.g. LEU)
Non-Nuclear Material Flow	HEAVY WATER PRODUCTION → POWER REACTORS GCR AGR HTGR LWGR LWR HWR FAST	Relation element representing the flow of non-nuclear material.
Association	REPROCESSING NON AQUEOUS AQUEOUS — CONVERSION CONV.1 CONV.2	Relation used to symbolize association of two activities other than nuclear or non-nuclear material flow. It is also used to associate other abstract elements such as indicators.

Table 4.3. Relation elements represented by arrows symbolizing the flow of nuclear material and non-nuclear material. Undirected relation represents association of two elements

1. It is used to represent the overall nuclear programme and provide an overview. This is a high-level model, which can be considered as computation independent model (CIM). It serves for mapping and depicting the overall nuclear processes taking place in a state. It can be used as an entry model to more detailed models and based on the classification suggested in [12] belongs to so called knowledge management models that are to be mainly used and

interpreted by humans i.e. safeguards analysts, inspectors.

2. It can be used to model nuclear weapons acquisition paths. Using the notation to identify different nuclear activities this modelling language can be used to represent the weapons acquisition path. It represents a process model based on syntax shown in the previously presented meta-model. In order to leverage a great number of existing algorithms applicable to business processes some of the constructs and notation is based on the BPMN. This model consists of constructs also known in BPMN as Events: *Start*, *End* and *Gateway* where logical operators such as OR, AND XOR can be used) [75]. Nuclear Activities represented with notation as rectangles are activities such as mining and milling, fuel fabrication, enrichment, reprocessing, reactors and research reactors. These activities can be further described at a subprocess level using the same notation. Specific technologies used during each activity are represented by highlighting with a predefined colour the development scale. For example for activity Enrichment - MLIS can be selected as the technology that can be shown as yellow if the technology is in development phase or with green if the technology is in production. Apparently indicating no colour means that the country does not possess this technology and it is not potentially a part of their weapons grade material acquisition path.

The first use case of using the model is to be *descriptive* of the nuclear programme in a country whereas the second one can be used to create also *prescriptive* models. The formal representation of the NFCM will be based on Pattern Theory as presented in [13] and detailed in the next chapter of this thesis with graphical and mathematical formalism. Figure 4.10 shows an example of the formalism using pattern theory generators to graphically represent the post-conversion nuclear activity.

Examples of two versions of models used to provide an overview of the nuclear programme are shown in Figures 4.11 and 4.12. Model shows a fictitious country **Ruritania** where the overall nuclear programme is shown as recommended by Liu et al in [1]. Ruritania is thought to have Enrichment, Fuel Fabrication and Reactors that characterize its capability. The modeller can choose to use a template where

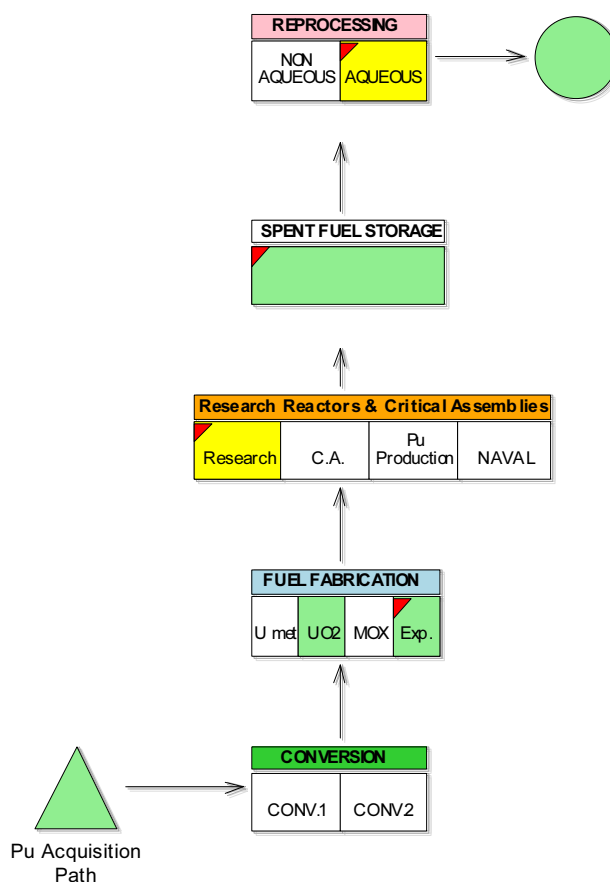


Figure 4.9. Simplified example of the NFCM used to represent an Pu Acquisition path in the state of Ruritania

by the activities which are not part of the states programme are also shown however are inactive (visually shown as colourless). The other possibility is to simply display the activities declared as present. Each of the activities is described with a set of attributes that offer specific facets of the activities and the technology used. This was a recommendation from STR-325 where technologies and related activities are further characterized as not being declared, in development or at research phase only. Relation classes such as nuclear material and non-nuclear material are an extension to the modelling primitives suggested. They represent a control flow and describe the type of material flowing from one activity to the other giving a process-based view of the nuclear activities. One important question the model designer

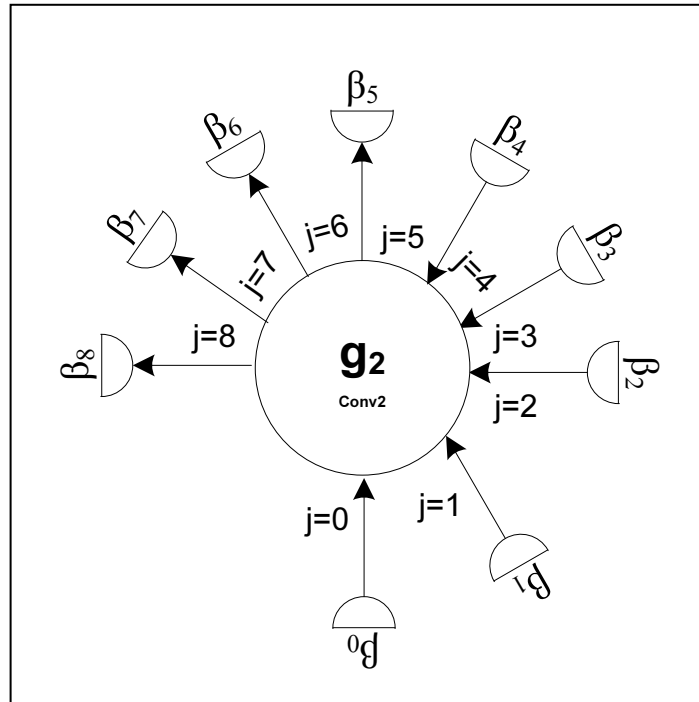


Figure 4.10. An example of graphical formalism used to describe modelling elements with generators based on Pattern Theory. The example shown represents the nuclear activity *post-Conversion or Conversion 2* which has nuclear material flowing to and from the activity.

should ask especially when creating overview models (case 1) is do such models represent aspects that cannot be obviously derived through existing information systems and other means. It is then that use of models becomes economically and operationally feasible.

In the second example (Fig. 4.12) a more detailed view of the nuclear process model is shown. As previously described the modelling primitives are the same so to avoid a great number of modelling elements. The model of Ruritania shows the potential acquisition path for the state Ruritania. The model has a *Start* event and an *End* Event which in the context of the acquisition path usually begins with *Mining and Milling* as a starting event and Pu or HEU to symbolize the end of the acquisition path which is equivalent to acquiring the material for building a

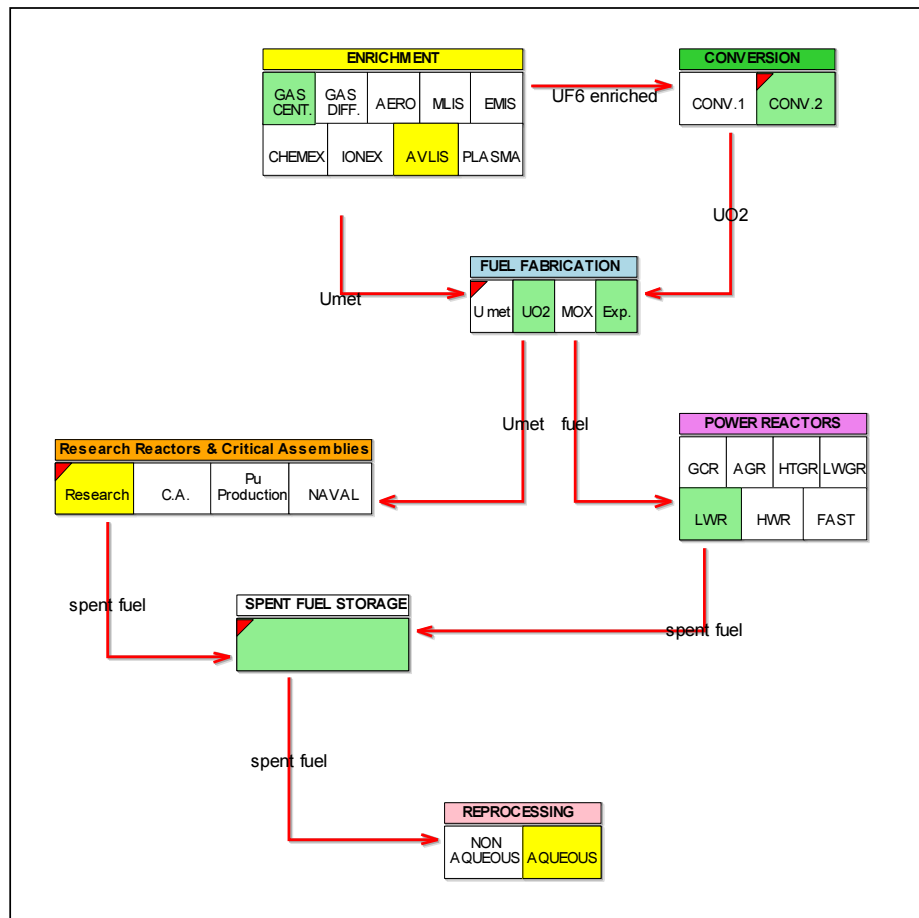


Figure 4.11. Ruritania's Nuclear Programme Overview showing the nuclear material flow

nuclear explosive device. The red flag shown on the Fuel Fabrication:Exp or Spent Fuel indicates a potential inconsistency. This attribute offers visual representation of activities that can be potentially abused or have some question or inconsistency related to them. This will provide a capability of completely describing existing and potential paths of acquiring weapons grade nuclear material. These models can be used to describe the nuclear process in a state *as is* or *could be* (differently named compared to the commonly known "should be" in process modelling). The two states are equivalent to the terminology used in business process modelling where we model *as is* and *should be* however not politically appropriate here. This model can be used for all purposes required by the STR-325 where the basic paradigm says

that the assessment of activities should address the following sequential questions [1]:

1. What capabilities and experiences exist in a State declared nuclear fuel cycle, and how would these likely be used if the State decided to pursue the acquisition of weapons-usable material?
2. What capabilities, other than currently declared, would have to be developed for that purpose?
3. Are there any development activities going on (declared or undeclared) in the State that might be related to such capabilities?
4. To what extent have these development activities proceeded?

Firstly the existing capabilities can be represented through the model and then models of missing capabilities that would potentially have to be developed can be represented using the modelling language. Modelling method is complemented by algorithms and mechanisms shown in the next chapter where formalism of representing the model is used to provision mathematical structures for applying algorithms (e.g. Dijkstra to determine the shortest path). The objective is to not only see modelling methods as chunks that can be melted into an information system but to also provide "functionality to use and evaluate" [7]. It is the objective to represent the nuclear fuel cycle using formalism other than graph but instead pattern theory. Algorithms based on this formalism can find application in evaluating nuclear fuel programmes such as the example model for Ruritania.

4.6.2 Nuclear Facility Model

One important component in nuclear verification that determines the design of a safeguards approach is the nuclear installations: their status (i.e. decommissioned etc.), their purpose and relation to other facilities in the state and outside. In order to complete the overview of the nuclear activities in a state the facility model is referenced from the Nuclear Fuel Cycle Model to show the facilities involved in performing the declared or potential undeclared activities. Such activities are mapped to one or more facilities or groups of facilities called sites. Another type

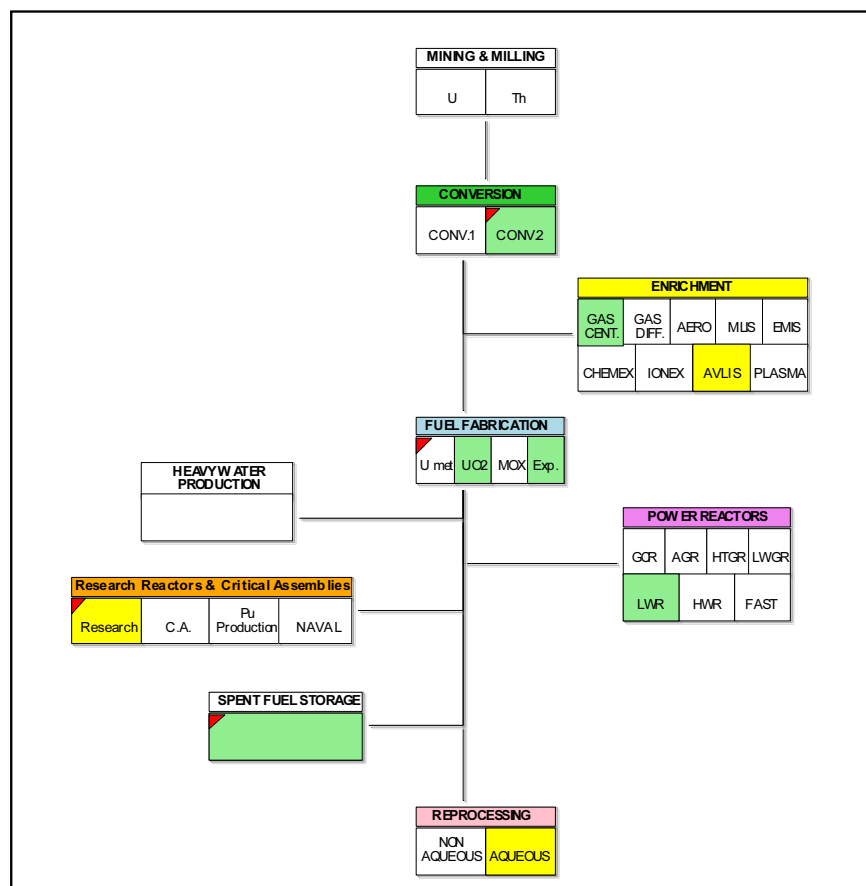


Figure 4.12. Ruritania's Nuclear Programme Overview showing only the association of activities

of grouping sometimes used in devising safeguards approaches is *sector*. Identified acquisition paths can point to existing facilities or non-existing facilities which would be needed for missing activities in the acquisition path.

Nuclear Facility Modelling is based on a modelling language to represent installations relevant to Safeguards based on the traditional agreement INFCIRC/153, the protocol additional INFCIRC/540 and states under the 66 agreement. A nuclear installation may be one of the following and is represented with the modelling element "Facility" [30]:

- Nuclear Facility - this can represent either reactors, critical facilities, plants for conversion, fabrication, reprocessing and for separation of isotopes. It can

also represent other facilities where there is considerable amounts of nuclear material as defined in the safeguards glossary [30].

- Uranium mine and concentration plants - explicitly mentioned since these locations are not required to be declared under the traditional safeguards and however under the articles of additional protocol must be declared.
- Locations Outside Facilities (LOFs) - installations outside the facility where there is considerable amount of nuclear material.
- Other Locations - Under the specific agreement INFCIRC/66 to which very few countries are signatory to this is equivalent to LOFs mentioned above. For the purpose of facility modelling in this framework this type of installation is used to represent any type of installation, which is not defined as a facility, LOF or a uranium mine and concentration plant. This modelling element can represent any other installations co-located at the site with the nuclear facilities [18].

Each installation whether a facility or LOF can be represented with specific attributes of the modelling element corresponding to installation codes per descriptions provided in [30]. For safeguards purposes there are also a set of phases in the lifecycle of a facility or generally speaking a nuclear installation, from the point when the decision is made to construct it until it has been decommissioned. One facet of the modelling element Facility is also the life cycle phase which can be one of the following: *pre-construction, construction, commissioning, operating, maintenance or modification, shut down, closed down and decommissioned*.

Another concept important in representing nuclear and other installations in a state is the *site* introduced under the additional protocol 540. It has been defined in details in [30] and represents delimited area in the design information provided by the state. Site is represented in the modelling language with an aggregation element. Facilities and LOFs represented within the aggregation are considered to be part of the site. The facility modelling language elements are shown in table 4.5.

In addition to the nuclear installation class instances of which are facilities or LOFs there are relation classes which represent the relationship between two

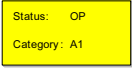
Element	Notation	Semantics
Facility		A nuclear Facility. Status shown distinguishes visually between facilities depending on their operational status: OP for operational and CD for decommissioned. The code represents the type of facility (e.g. A for power reactors)
LOF		Location Outside Facility. The element symbolizes also the operational status and type of LOF per classification defined in INFCIRC/153 and INFCIRC/540.
Other Location		It represents a building and any other type of location which may be only declared under additional protocol. It offers symbolism to represent any object which is not a facility or a LOF.
Aggregation		Represents logical grouping of nuclear installations. For example site, sector etc.
Note		This is unrestricted element which allows for free text, images and other media that can be embedded.

Table 4.4. Elements representing nuclear installations and their grouping in the of the Nuclear Facility Model

Element	Notation	Semantics
Transfer		Transfer is a relation class that shows the relationship between facilities, LOFs in terms of the material flow. The shipping and receiving facilities are shown with the letters "S" and "R"
Related		"Related" symbolizes an undefined relationship between any of the elements (installation) in the model. It can be used to represent assumptions or potential association of facilities within the State or outside (shown with a dotted line)

Table 4.5. Relation elements representing transfer or undefined relation between installations in a State and internationally.

facilities, LOFs, sites or even States. *Transfer* relation class entails the modelling element which represents the material transferred from one facility, site to the other. The relation class is characterized with edges that are labeled as "S" or "R" symbolizing which nuclear installation is the receiving one and which is the shipping facility. In case the same two facilities both receive and ship to each other this is represented by creating an additional transfer relation. To represent an undefined relationship between nuclear installations another relation *Related* can be used. Notation and semantics of models are shown in table 4.5.

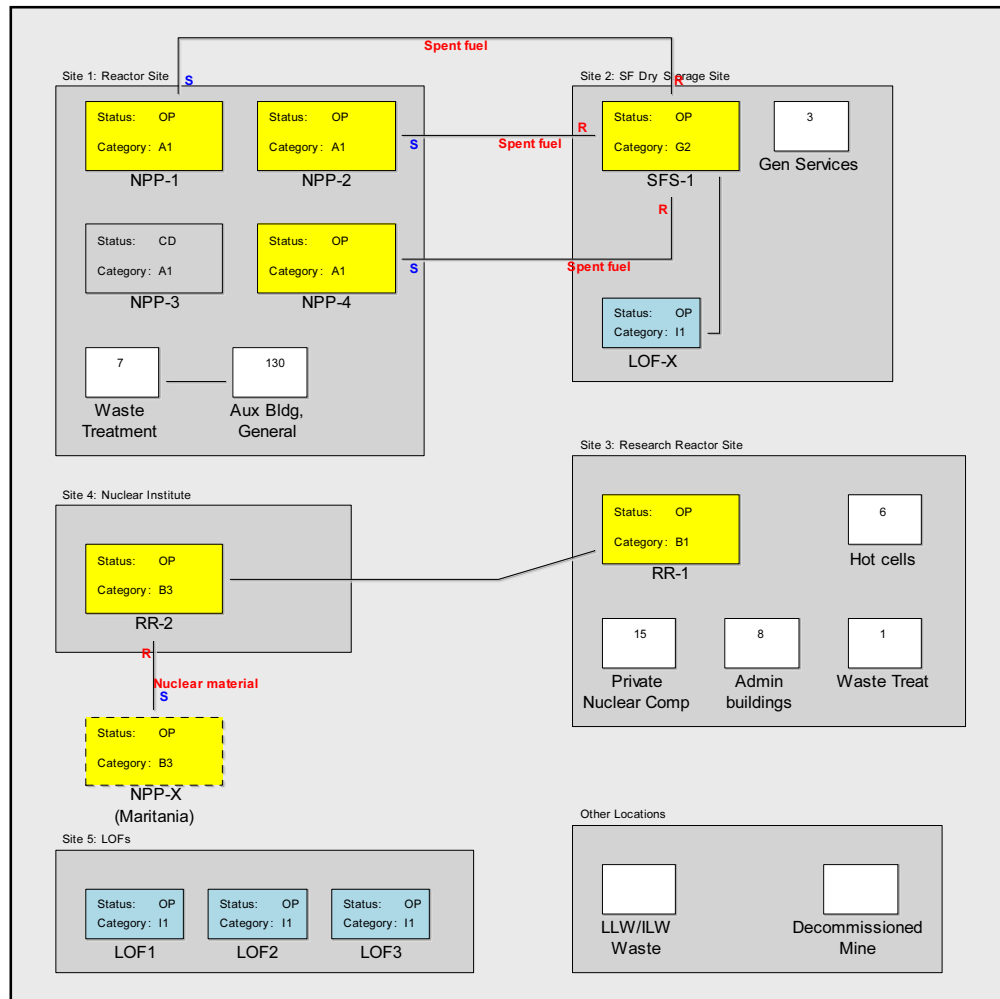


Figure 4.13. Example of using the Facility Modelling Language in representing nuclear facilities and sites in Ruritania

Figure 4.13 shows an example of the facility model where 5 sites are represented. In addition to a relation between facilities in a state there is also an example of a relationship between a facility in Ruritania and a facility in Urania (another fictitious state). Installations which are external to the state modeled are represented with a dotted line. The modelling language also allows representing buildings and *Other Locations* which are not per definition facilities or LOFs. This representation is important for activities such as Complementary Access (CA).

4.6.3 Organizational Inspection Model

This modelling language is used to represent the working environment and the organizational aspects of the inspectorate. Modelling elements are identical to elements commonly used to describe organizational structure in environment such as [76, 75]. It specifies the formal organizational units which in the Department of Safeguards are broken down to: *Department, Division, Section and Project or Unit*. It also specifies the roles and the individuals that are working within an organizational unit. Referencing the SG objectives and inspection processes, it represents an assignment mechanism where staff are associated to the objectives and inspection activities. An example of the inspection organizational model is shown in figure 4.14. Some of the notation is adopted from ADONIS and PROMOTE *working environment mode* [76, 9, 8, 41].

The inspection organization model is also supported by reference with languages which are a part of the PROMOTE method where knowledge and skills can be modeled. Associating individual staff the processes based on their skills and knowledge profile provides a knowledge view of the resources in the organization. Table 4.6 shows the elements of the Organizational Inspection Model.

The relation classes represented as elements of this model are: *"belongs to"*, *"has role"* and *"is subordinated"*. As shown in the example of figure 4.14 organizational units can be broken down to sub units which are subordinates. A person can belong to any of the units and is assigned a roles (e.g. knowledge manager) . One person can have more than one role (e.g. section head and process owner). Terminology is adapted to the working environment of the IAEA and the department of Safeguards.

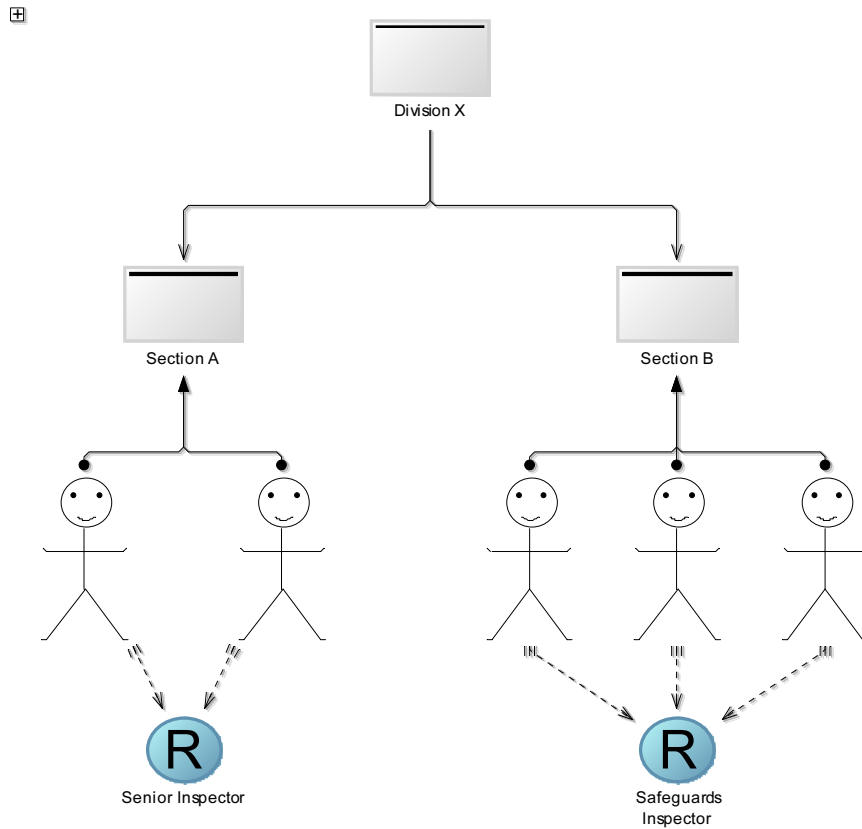


Figure 4.14. Example of the Inspection Organizational Model representing a general organizational unit at the inspectorate

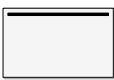
Element	Notation	Semantics
Role		Role represents the job of that the person. Every person or performed can be assigned to a single role or more.
Organizational Unit		Organizational unit can be a formal group in a organization such as Department, Division, Section or Unit.
Person		Symbolizes the person who performs a certain task by being assigned a role and belonging to a organizational unit.

Table 4.6. Elements of the Inspection Organizational Model.

4.6.4 Inspection Process Model

This is a modeling language to represent the business processes of the operational perspective. As mentioned in previous work [77] the preferred term is inspection process model. For the purpose of this study inspection process modelling is defined below where an important distinction is made with reference processes commonly created and already existing in organizations such as IAEA [46]:

”the exercise of representing inspection activities and used resources working together towards achieving inspection objectives efficiently and effectively in a structured and repeatable manner. Such process models are based on reference processes however are specifically modeled for a facility, site or state”

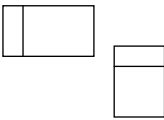
Element	Notation	Semantics
Sub process		Is a process that is included within another process. Represents symbolism for the decomposition of a business process. Repeatable processes can be called or complex process can be decomposed.
I-Activity		I-Activities represent inspection tasks executed in a business process.
Aggregation		It represents logical grouping and structuring of content on the diagram.
Note		This is unrestricted element which allows for free text, images and other media that can be embedded.
Swimlane		Horizontal and vertical swimlanes can be used to organize and categorize activities.

Table 4.7. Activity and other elements of the Inspection Process Model based on ADONIS and BPMN

It consists of elements that are common to modelling business processes using the BPMN notation from BPMI [75]. The inspection process model is based on

the notation and syntax used also in ADONIS [76]. It entails same elements used in representing a business process however semantically customized for inspection process modelling. This modelling language represents activities performed by safeguards inspectors as specified in the safeguards approach. Elements of this modelling language are gateways such as *start*, *end*, *parallelity*, *decision* and *merge*. Moreover, *activity* and other elements are used to represent logical grouping of activities and content on the drawing area (i.e. swimlane, aggregation). Elements of the inspection process model, their notation and semantics are shown in tables 4.7 and 4.8.

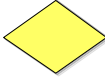
Element	Notation	Semantics
Process start		Symbolizes the beginning of a business process. There has to be exactly one start element for each business process.
Process end		Represents the process end. There can be only one end element in the diagram.
Decision		It is also referred to as complex gateway. It triggers one of more branches based on an evaluated condition.
Parallelity		Represents the symbolism for representing “AND” gateway. All sequence flows out of this gateway are activated simultaneously.
Merging		Is the element where more execution paths are merged. It awaits one of more incoming branches to complete.

Table 4.8. Gateway elements of the Inspection Process Model based on ADONIS and BPMN

Inspection process models in the inspection modelling framework are also utilized as an entry point to knowledge management process models (KMPs), modelled with PROMOTE. Based on the Process Oriented Knowledge Management (POKM) approach and with the help of a knowledge management modelling language provided by PROMOTE, inspection knowledge intensive activities will refer-

ence Knowledge Management Process (KMP) models which describe KM activities and give a process-oriented view of KM. Knowledge Intensive Tasks (KITs) and referenced KMPs exemplified later in the chapter.

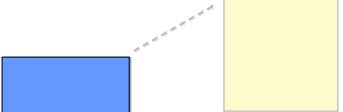
Element	Notation	Semantics
Subsequent		Represents the sequence flow between activities
has note		Represents a connector extending a note from one of the inspection process modelling elements.

Table 4.9. Relation elements of the Inspection Process Model based on ADONIS and BPMN

Other elements of the inspection process model are the relation classes which typically in the business process model consist of the main relation *subsequent*. Subsequent is also used in IPM to represent the sequence flow of activities. This elements and *has note* used for relating notes with free text and images are shown in table 4.9.

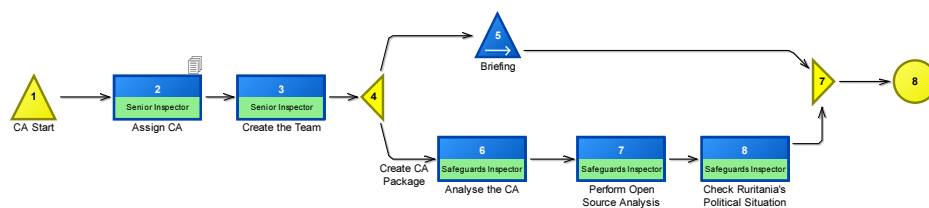


Figure 4.15. Example of a Inspection Process Model based on ADONIS and BPMN

4.6.5 Inspection Objectives Model

Another modelling language in the set of inspection modelling languages is the Inspection Objectives Model (IOM). Before describing the modelling elements of this language the purpose of the language in the framework will be discussed. Furthermore, a conceptual background of the language will be set forth showing how inspection objectives are represented by having higher level objectives and functional objectives at the subsequent level. Linking objectives at all layers is meant to provide traceability, adaptability and means to measure the performance of the inspection activities in fulfilling safeguards objectives. Furthermore, objectives can be considered as criteria which is particularly important under the undergoing shift to information driven safeguards.

Generally the *objectives modelling* or as commonly known *goal modelling* is referred to in the literature [78, 67, 72] in the context of process modelling. Before proceeding it is important to define the terms *objective* and *goal* in the context of modelling. Also, compare the two which will reflect the choice of terminology made to represent inspection objectives, namely the *Inspection Objectives Modelling (IOM)*.

Term *Goal* in the Princeton dictionary is defined as state of affairs that a plan is intended to achieve. From a more system based perspective in [79, 67] "*goals express intentions and capture the reasons of the system to be built*". Lamswerde defines goals as an objective a system under study must achieve. It corresponds to an objective a system should achieve through cooperation of agents in the software to be [80]. Objectives are also defined as statements that lead to the attainment of goals and in Requirements Engineering (RE) related literature the two terms are used interchangeably. One of the definitions from Webster's is "*something towards which effort is directed: an aim, goal, or end of action*". The term objective is also used in decision science where Keeney defines the term objective as "*a statement of something that one desires to achieve*" [81]. Also, it "*generally indicates a direction in which we should strive to do better*" [82]. Most of the researchers in the field of requirements engineering use the term goal whereas decision science is characterized with the term objective.

Objectives in the view of Hurri are measurable and compare to criteria. In contrast goals are less measurable and difficult to quantify their attainment [82].

However, it is common that the two are used interchangeably. The preferred term in this study will be *objectives* and it is important to look at objectives as criteria in the context of Safeguards under IS under the absence of the traditional criteria based on significant quantity required to build a nuclear weapon and timeliness representing the time it takes to build it.

Some of the reasons why the term objective is preferred for the conceptual verification framework are:

- the term objective is already commonly used in the implementation of safeguards to express achievements and purpose of inspection activities [45, 18, 30].
- term objectives should not be mixed with inspection goals which have a specific meaning in the nuclear inspection domain. There are two inspection goals which represent performance targets. Significant quantity (SQ) and timeliness discussed in previous chapter [45].
- the purpose of the inspection objectives modelling is not focused on requirements engineering and software development but it rather serves as a technique for representation to assist inspection decision making and process design.
- the term objectives can also represent criteria used for evaluating the effectiveness of safeguards measures.

4.6.5.1 Modelling Goals and Objectives

Modeling goals and objectives is a research field in development with years of work performed on [8, 83, 84, 85]. Literature review shows that there are two main applications where goals or objectives modelling is applied: *decision science* and *requirements engineering (RE)*. In requirements engineering goals provide various reasoning schemes [86]. With the goal-oriented RE we can check whether requirements are complete and correct ensured through the operationalization of objectives [62].

From a RE point of view goals/objectives are grouped in two main categories *functional* and *non-functional*. In a software engineering sense the two categories

relate to the functional and non-functional requirements. Additionally, goals can have attributes such as name, specification, priority and can be linked [80].

4.6.5.2 Objectives and Process Modelling

The conceptual relationship between the process modelling and objectives as a practices on which modelling is based occurs as covered in literature [67, 80, 78, 87]. It is especially discussed in the field of RE. Requirements engineering (RE) interconnects activities such as domain analysis, elicitation, negotiation/agreement, specification/documentation and evolution. All of these activities can be supported with approaches such as goal orientation in defining complete and correct requirements [67]. Here the focus is not so much specifying requirements but rather through an objectives-based technique to design measurable objectives and inspection processes that best contribute to strategic and lower level technical objectives. Also, subsequently contribute to higher level objectives.

Kueng and Kawalek state that goals or objectives modelling "is a critical step in the creation of useful process models." Among others it is said that goals/objectives modelling is important because [67]:

- "we state what we want to achieve so that we are able to define necessary activities which business process should encompass" - in our case inspection processes
- "understanding of goals is essential in selecting the best design alternative"
- we can evaluate the operating quality of processes
- "clear expression of goals makes it easier to comprehend the organizational changes that must accompany a business process redesign."

According to Neiger et al and the research they performed, process and objectives modelling can be seen as one of the three approaches:

- *State-based approach* where the notion of state exists as where process models are a dynamic "system that moves in the space of all possible states until it reaches the final state (goal)" [88].

- *Requirements Engineering* which is very well covered and still a current field of study. Here goal oriented view provisions for completeness in eliciting. It related to more advanced aspects related to autonomic systems [89, 90].
- *Decision Analysis* approach actualised in the context of goal modelling through work of Neiger and Churilov [91]. Structuring and linking means objectives to fundamental objectives based on the Value Focused Thinking (VFT) framework of Keeney [81]. This represents a different approach from the two above since the focus is not on the process models as configuration means for running workflows nor does it serve the common purpose of deriving accurate requirements. The aim is to introduce objective-based view in decision making related to the design of process models. The position we prefer to take in our framework.

Value-Focused Thinking (VFT) is a philosophy introduced by Ralph Keeney. According to Keeney "values are what we fundamentally care about in decision making". Alternatives are simply the means we use to obtain our values. This approach is based on three major principles that guide decision making in a step-wise fashion: start with values; use values to generate better alternatives and use values to evaluate the alternatives [81].

4.6.5.3 Lower-level Functional and Process Objectives

The next step in defining how the objectives are achieved and measured is to establish a link between the so called fundamental objectives at a more abstract layer and the concrete activity objectives. Neiger et al make an attempt to link the fundamental objectives to the process and functional objectives through decomposition and refinement/reduction [92]. Fundamental and process objectives are considered as a subset of means objectives therefore relating the two indirectly. Work presented shows a link to the EPC processes and functions. EPC is a modelling language based on petri-nets used under ARIS framework which already contains modelling elements such as goals that can be decomposed using a framework such as VFT. In ARIS functions are defined as "technical tasks performed on an object to support a company goal". This approach is however presented under

the assumption that company goals and objectives are known to the modeller in advance and are supported by functions [93].

Korherr and List focus on the issue of goal based process modelling and technical aspects by trying to extend the meta model of both EPC and BPMN with organizational and goal concepts allowing an enhanced "goal-sensitive" representation of BPMN and EPC. Their work is more focused on measurement of activities or functions which is based on the existence of goals that these activities/functions have to fulfill. In comparison to EPC, in BPMN as specified by BPMI there is no goal modelling element [75]. A related approach in industry known from Whitestein Technologies proposes a goal-oriented business process modelling and execution under the name GO-BPMN. Here the objective is to extend not only business process modelling but also business process execution. Each goal is associated to one or more alternative plans which can satisfy the goal. Run-time execution is performed on the best path depending on specified conditions [94, 95, 87].

Since inspection process modelling is mainly based on the BPMN notation, semantics and syntax, inspection objectives modelling is considered as the integration layer between the domain specific nuclear process models and domain independent inspection process models. The aim is not to change the notation with new elements but to rather enhance the integration of meta-models.

Figure 4.5 shows the meta-model of the inspection process model and the inspection organization model also important for representing inspection objectives. Processes, activities and tasks can reference at most one objective whereas the same objectives can be references by more than one different activity or process. Since we also need to have means of measuring the performance against the defined goals, attributes that represent criteria like questions will be embedded to the means objectives modelled. In addition to the modelling elements of the language the aim is to present inspection objectives that may be achievable through alternative paths. Also the idea is to provide a procedure for the decomposition of higher-level objectives or fundamental objectives and linking them to the inspection process and activity level objectives.

In order to provide for both refinement and decision path there has to be formalism such as the one suggested by Neiger or Korherr and List [96]. Neiger et al suggest logical connectors between the means objectives and the subsequent

process and function objectives of EPC. With a level of formality objectives models can be used for decision analysis in process design but also for automation by inferring [89].

The lowest level of fundamental objectives is the highest level of means objectives. Any leaf objectives must be connected to at least one process, activity or task implying the execution of each contributes towards the higher level fundamental objectives. Objectives may be independent of each other or means objectives may have independent goals that are met by means that are not related to any of the other. This will commonly be handled by modelling a separate inspection objectives model. The logical connectors between the objectives and processes are represented with AND/OR refinement as suggested in [92]. The selected trajectory of lowest level, atomic activity objectives represents the so called inspection pathway which can be evaluated with measures for each objectives or through some aggregation schema [16].

4.6.5.4 Safeguards Objectives

As most other organizations in the department of Safeguards there are goals of higher level that reflect the vision of the organization and there are also more specific goals which are measurable and are fulfilled on daily basis. Under Inspection Objectives Modelling only objectives related to the inspection activities and the nuclear verification regime of the IAEA will be discussed. It is though not limited to the department and can be extended as a framework across the whole IAEA. Strategic aspects of the verification programme are discussed in more detail in Chapter 2.

Department of Safeguards seeks objectives as defined in the strategic plan. These objectives represent the direction which the department intends to follow in order to meet the overall organizational goals in agreement with the mission statement of the IAEA and the priorities set by the Board of Governors. The identified high level objectives (here named goals) for Safeguards according to the IAEA' Medium Term Strategy are [17]:

1. Goal C1: Assurances to the international community of the peaceful use of nuclear energy

2. Goal C2: Contribute as appropriate to effective verification of nuclear arms control and reduction agreements, including nuclear disarmament

To ensure that these objectives are achieved and that efforts within the organization are aligned, inspection objectives modelling should provide means of representing the relationship between higher level objectives and lower level objectives which are measurable. Furthermore, measurable objectives need to be integrated with inspection activities at the process activity and task level. Such an approach offers the advantage of:

- documentation of objectives and the means to meet them
- serve as a basis for goal-based requirements engineering projects in the department
- allow flexibility and adaptability of inspection processes with changes in organizational objectives
- serve as a tool for decision making during inspection process design and evaluation
- creating measurable criteria-like inspection objectives

In order to implement such an approach there has to be a relationship between the *fundamental objectives* and *functional* or in the case of BPMN formalism, activity and task objectives [97, 81]. So called fundamental objectives as discussed by Keeney represent the goals defined in a decision making context. The *means objectives* represent the methods for achieving fundamental objectives. Neiger et al extend this approach using the Value-Focused Thinking (VFT) technique with a conceptual link to the next level of means objectives namely functional and process objectives defined in ARIS and represented with the EPC process modelling [93].

Figure 4.16 shows the decomposition of safeguards objectives as proposed by Eckhard et al where higher level general state objectives are decomposed to so called technical objectives in a process that asks at each level below the predefined General State-Level Objectives (GSLOs) the questions:

- *Where does the inspection need to be done?* and

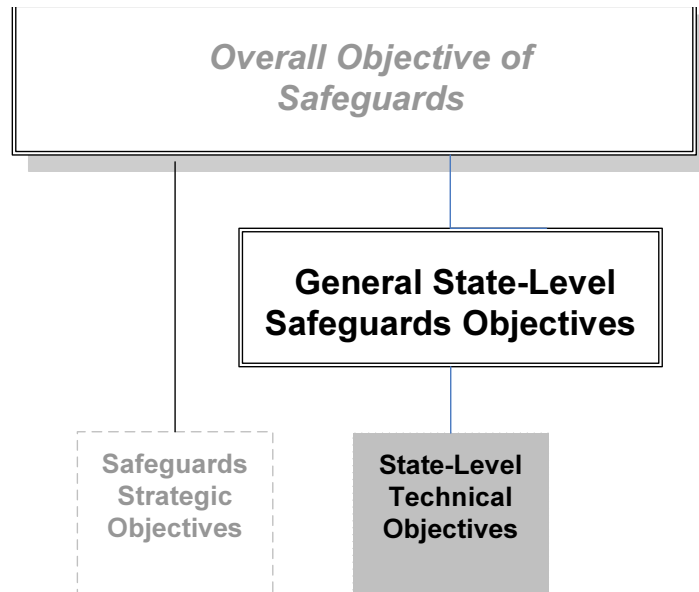


Figure 4.16. SG Objectives Structure from Eckhard et al. Safeguards Objectives are followed by General State-Level Objectives out of which State-Level Technical Objectives are derived. Other Safeguards Strategic Objectives are seen at the same level of the technical activities.

- *What needs to be done to meet the objective?* (i.e. detection of undeclared activities and material in a state)

The later is a rather obvious question however it relates to the first question, which in the structure of inspection objectives is an aspect related to the facility in question. Most of the technical objectives are based on the type of facility that needs to be inspected. This process has generated 42 objectives, which can be applied to one of the possible scenarios in verifying a state.

Hurri claims that the main problem when dealing with the objectives decomposition is the generation of objectives and the structuring [82]. The generation of inspection objectives is well covered by the facility-type-based process however it still lacks clarity in how the objectives are structured and does not consider their link to inspection process objectives. The more natural way of looking at the inspection objectives is by asking what we want to achieve and then think how were going to do this. The "where" part will be implicit using the structuring proposed.

In literature as it is discussed the goals are usually decomposed to lower level

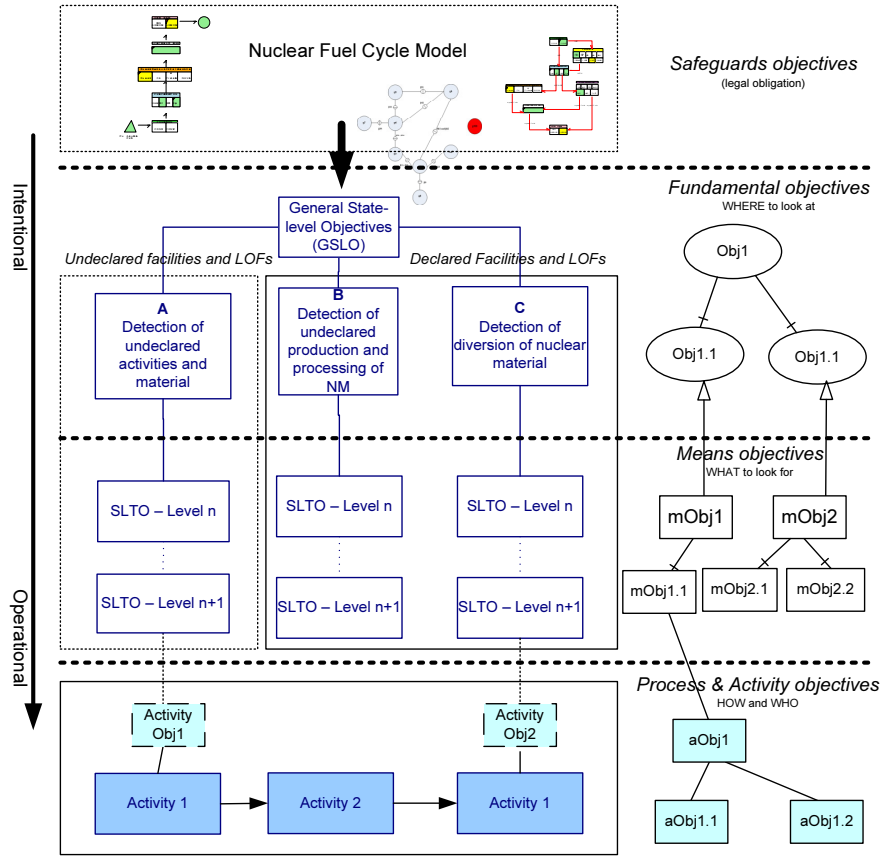


Figure 4.17. SG Objectives decomposition and the corresponding decomposition based on VFT. Higher level models are decomposed to SG Objectives according to the scheme proposed by Eckhard et al. SG Objectives are linked to lower level activities to provision objectives based modelling of processes.

goals that represent the methods to achieve these. Using the VFT we could characterize the GSLO objectives as fundamental objectives. They represent a hierarchy of general objectives that add value in a specific decision context [91, 67]. Decomposing higher level safeguards objectives to technical objectives can be mapped to fundamental and means objectives represented in the VFT with the casually related means ends objective network.

Figure 4.17 shows the conceptual relation between the VFT framework and the predefined safeguards objectives as suggested in the approach of Neiger and Churilov [91]. In a top down manner fundamental objectives are derived from the

state level analysis of weapons acquisition paths and legally binding agreement between the IAEA and a member state. Subsequently, means objectives are linked to the processes and activity objectives which in the case of inspection modelling are represented through a combination of models that show how and who performs activities that are crucial to the attainment of inspection objectives. This will guide the generation of enhanced objective sensitive inspection models that operationalize verification knowledge in contrast to generic reference processes presently used.

4.6.5.5 Suggested Objective-based Approach

In order to have formalism which will allow for the NFCM activities as illustrated in 4.17 to be translated into state level technical objectives we need to create a link between the elements of the nuclear fuel cycle model and the structural elements of the objectives model. The idea is to extend the inspection process model discussed in more details before with another attribute *activity objective* which will reference the objective. Therefore offering an integrated modeling environment that allows for methodical inspection process modeling based on objectives that are decomposed from higher level safeguards objectives. This needs to be done by the domain expert based on the results of the analysis performed on the NFCM model.

Nuclear Fuel Cycle Model has a formalised syntax as defined in the inspection meta-model. Using the pattern theory formalism analysis will be performed with algorithms that evaluate valid generator configurations in order to identify different acquisition paths of HEU, Pu. Details of representing this language with generators is provided in the next section. The basic premises here is to move transparently from higher abstraction layers to lower ones by transforming one model into another without loss of semantics captured from the domain experts with the NFCM. For example, if a certain acquisition path is discovered in a country this can be represented by using the NFCM model. Each of the represented nuclear activities references existing nuclear installations (facilities, LOFs). By starting with the fundamental questions already known from work of Eckhard et al the two questions that will lead to the decomposition and discovery of means objectives for state level safeguards are:

- Q1: *Where* is the [*declared/potential*] activity taking place
- Q2: *What* needs to be looked at that location

The structure of the state-level objectives can be represented with a modelling language which consists of 5 elements. These elements are based on the VFT as well as principles adopted from other methodologies such as i*, KAOS and a new method presented in the project BREIN [8, 85]. First element of the language is a *goal* here known as objective which can be either soft or hard as defined in [85]. In the inspection objectives model this distinction is not made. Each objective can be decomposed into subobjectives which are connected to the super-objective through logical connectors AND/OR. The subobjectives can be met with means objectives, a relation represented through mean-ends connectors. Furthermore, actors who are responsible for each of the objectives can be identified. Another element is the actor boundary which indicates the scope of responsibility for the actor.

If we now look at the technical objectives at the state level as described by Eckhard in [98] the mapping between these objectives and the modelling elements of the inspection objectives model are described:

General state-level objectives (GSLO) as well as state-level technical objectives (SLTO) can be modelled using the *Objective* element represented by an ellipse. The state level technical objectives can be represented using the means end connector pointing to the means of fulfilling these objectives or the technical objectives. The means objectives referred to in VFT can be further broken down and represent the link to the activities of a inspection process model.

Steps required for decomposition objectives and subsequent mapping to inspection activities are:

1. Identify the objectives which need to be further decomposed based on the generated list of objectives
2. Decompose the state-level objectives or means objectives generated from the nuclear fuel cycle model. Decompose them to the level reasonable [72].
3. Model the network of objectives such that all state level objectives are broken down to means objectives using the logical connectors OR/AND

4. Reference means objectives to processes or activities.

4.6.5.6 Elements of the Inspection Objectives Modelling Language

In this section elements of the Inspection Objectives Model will be shown. Some of the elements and corresponding notation used for this modelling language were adapted from i* as detailed in [85]. The meta-model of this language discussed earlier includes specific concepts related to the safeguards objectives and relies on the decomposition of objectives and their relation to business processes presented in work from [91].

Element	Notation	Semantics
Objective		Objective symbolizes fundamental and lower level goals. In the inspection modelling framework it represents the general state level objectives (GSLO) and state level technical objectives (SLTO)
Means objective		Means objectives represent the methods for achieving the higher level objectives or fundamental objectives. They are generated by asking the questions where and what.
Actor		Represents a person or role that is responsible for performing the tasks for achieving the objectives.
Actor boundary		Marks the boundary for which the actor is responsible. It groups objectives and means objectives.

Table 4.10. Elements of the inspection objectives model. Hierarchically structured objectives and methods for achieving them are modelled using the elements objective and means objective

Table 4.10 shows the notation and semantics for *objectives and means objectives*. Objectives are elements representing higher level objectives (e.g. fundamental as classified in VFT). The means objectives are those that satisfy higher level objectives. In the context of decision making this breakdown is adjustable to state level objectives and technical objectives in safeguards. Finally, means objectives reference processes, tasks or a group of processes or tasks enabling operationalization of objectives.

Furthermore, the relation classes of this model are shown. They consist of a

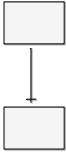
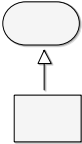
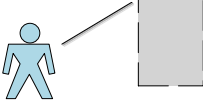
Element	Notation	Semantics
Decomposition		Decomposition link is used to hierarchically structure objectives: means objectives. The horizontal link is placed on the side of the decomposed element.
Means-end		Means-end relation represents the link between means objectives and objectives. It symbolises the method which is used to achieve the objective.
Is responsible		Represents a person or role that is responsible for performing tasks for achieving the objectives.

Table 4.11. Relation elements in the Inspection Objectives Modelling language.

decomposition relation and means-end link. Decomposition is used to hierarchically structure the means objectives. Means end relation is used to represent which objective is satisfied by which means objective representing methods of achieving higher level fundamental objectives. Notation used for the relation classes was adopted from Yu's i-star (i*) modelling language mainly focused on goal oriented requirements engineering [85].

4.7 Knowledge Modelling Language: PROMOTE

Modelling knowledge management is a part of a methodology PROMOTE. Under the assumption that knowledge management has direct impact on the performance of the business, business processes are indirectly linked to knowledge products [65]. The PROMOTE modelling language consists of a set of languages that help describe all aspects of knowledge management. The starting point is the business process model which leads to knowledge products and activities that generate these products. As described it models four dimensions of knowledge management:

Model	Description
<i>Knowledge Product Model</i>	Represent knowledge products offering both a product view of knowledge as well as process view by being loosely coupled with business/inspection process models.
<i>Knowledge Management Process Model</i>	Used to represent the sequence of activities needed for creating knowledge products.
<i>Knowledge Structure Model</i>	Is used to represent knowledge space in a form of structures whether is topics or other concepts that can bring clarity to relations of object in the knowledge space.
<i>Knowledge Map Model</i>	Represents an overview of knowledge activities, products and resources. It provides a bird eye view of the knowledge modelled.
<i>Skill Environment Model</i>	A knowledge view of the working environment where performers and roles are modelled by considering skills and profiles of employees needed to define knowledge roles.
<i>OWL/SWRL</i>	Extension of the PROMOTE language with Ontology Web Language and Semantic Web Rule Language. The two can be used for context aware BPEL workflow execution.

Table 4.12. Models of the PROMOTE Approach integrated in the inspection modelling framework to represent the Knowledge Management perspective.

The approach suggested in the framework is to identify the products of the inspection processes that can be modeled using the PROMOTE language. Products can be electronic or even human such as Experts. Other products can be search engines, technical reports and other products which need to be managed as explicit knowledge and in terms of knowledge activities that create them [8, 9].

4.8 Technology Modelling Language

This perspective of the modelling framework is rather vaguely named technology not to restrict it to modelling only information and communication technologies. In the domain of nuclear inspections there is also a great amount of hardware and software which are outside of the typical information systems boundary in a organization. They serve as technology for data collection and analysis and can contain

a great amount of knowledge in performing measurements and algorithm based calculations for Non-Destructive Assey (NDA) analysis. More often than not such equipment is developed by third party vendors which built and customized products for use only by the IAEA. Modelling methods and a model driven approach in general can be used to bridge the knowledge gap between inspectors in performing their duties in the field and suppliers of such equipment. Models can serve as requirements to the development and enhancement of new and existing equipment. They can also be modelled in order to aim for efficiency where technology can play an important role.

Next sections briefly look at UML and other modelling languages that can support the technology perspective of the framework.

4.8.1 Unified Modelling Language

UML in this framework is represented as the language of choice for modelling the technology aspect. As proposed by OMG , UML models can be used to also to represent abstractions in support of systems development. With the introduction of MDA, this language can be used to create Platform Independent Models that can be transformed to mode detailed models and eventually source code [100]. The historical challenge of continuous technology upgrade can be met with models that offer abstraction good enough to capture formal elements of the systems while providing possibilities to leverage new platforms and port existing applications.

Although UML can be also used to represent business activities (or the business layer), languages chosen and presented so far under the operational perspective are not limited to the documentation and specification for developing systems. In the inspection modelling framework UML models are used to represent more technical layers. Mapping higher level models of the operational perspective to technical models represented with the UML language is represents a challenge due to the great number of concepts and modelling elements that need to be semantically translated to UML models that can generate source code. Since the objective is not to generate code, the inspection modelling framework is not limited to also provide such a functionality. Solution to interoperability of these models is made easier by using the necessary formalism when representing inspection models. This

problem requires a formalisation of modelling layer which rests between inspection operational models and UML models. A good candidate for such a formalism is pattern theory which is based on so called generators. These constructs can be represented also with a graphical formalism and can be mathematically represented therefore supporting transformation and integration of models not only syntactically but also semantically by using algebraic constructs and algorithms thereof.

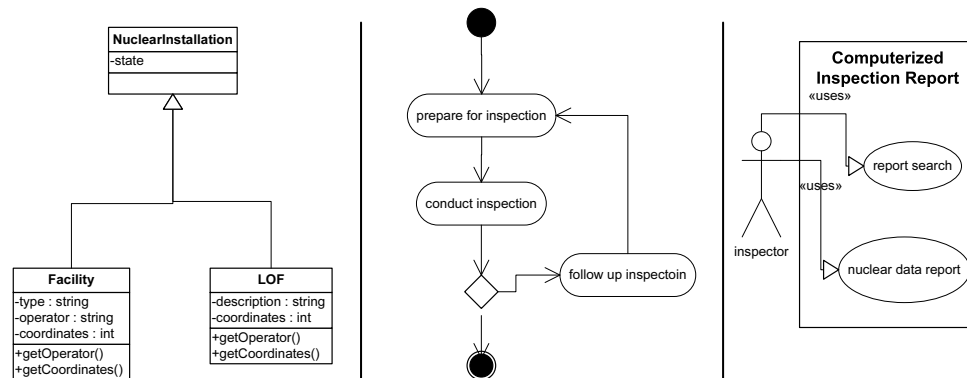


Figure 4.19. Simplified examples of UML models. Starting from left to right the examples show an instance of the class, activity and a use case model.

According to OMG UML 2.0 identifies 13 types of diagrams which are grouped into three categories. The three categories are *Structure Diagrams*, *Behavior Diagrams* and *Interaction Diagrams*. Structure diagrams represent the static application structure and include diagrams such as *Class Diagram*, *Object Diagram*, *Component Diagram* etc. The diagrams that represent behavioural aspects include well know *Use Case Diagram*, *Activity Diagram* and the *State Machine Diagram*. Interaction Diagrams on the other hand which are derived from more general Behaviour diagrams include *Sequence Diagram*, *Communication Diagram*, *Timing Diagram* and *Interaction Overview Diagram* [49]. Figure 4.19 shows some examples of UML diagrams that are also applicable under the inspection modelling framework.

Details of each type of diagram based on the modelling language will not be covered here. Specifications and in depth description of the language and its use

is offered by OMG in [100].

Formalization with Pattern Theory

As discussed in previous chapters the level of formalism required for a model depends on the intended purpose and expected results of its processing. As an example of a formalism that can be used in addition to the meta-modelling already shown is the known Pattern Theory (PT). Other formalisms through the use of graphs or petri nets are also possible however this thesis will contribute by defining the formalization elements based on PT. As the application domain in this research is nuclear verification the chosen model type to which the formalism will be applied is the Nuclear Fuel Cycle Process Model (NFCM). The intention is to process these models in order to check for their consistency or automate the generation of safeguards objectives inferred from the model. This is only one example of processing that can be achieved based on rules such as "if x nuclear activity takes place then activity y can follow". The task of automatically generating objectives from existing models does not in itself represent a complex job however the formalization of rules is demanding and requires domain knowledge. This example of formalization is meant to serve as basis for applying more complex algorithms (e.g. stochastic approach). Moreover, the identified constructs based on the theory should be useful for formalizing any modelling language provided that it adheres to certain level of formalism (models as defined in OMI).

This theory stemming from applied mathematics field offers graphical and mathematical formalism, which may bring us a step forward in closing the gap between a machine processable languages and easy to use domain/specific modelling languages. Through the use of so called generators that represent atomic

elements, in our case diagrammatic modelling language primitives, principles of regularity can be formalized. Generators can be positive pixel values in an image, states in Markov Chain, geometric objects such as vectors and surface elements, or rewriting rules in language theory. Rules of transformation are the generators (formal grammars). Transformation allowed by the rules are constrained by the consistency that is placed using the bonds between the generating rules [101].

5.1 Pattern Theory Elements

The theory presented was first introduced by Grenander in [13]. Next a canonical introduction will be provided presenting the algebraic constructs that can describe the structure of the generators as well as their admissible combination into configurations.

Properties of a generator are defined with in-bonds, out-bonds and attributes. To a given generator corresponds the arity $\omega(g)$. The arity tells us the maximum number of connections to the generator and represents the sum of in-arity and the out-arity. Generators can appear more than once in a configuration. To keep them separate identifying marks as parts of attributes are used. Basic elements of a generator are graphically depicted in Figure 5.1. Direction of the bonds in-wards or out-wards can also be represented with an arrow. Properties of the generator shown graphically can be therefore described as follows:

$$\begin{aligned}\omega_{in}(g) &= 2, \omega_{out}(g) = 2 \\ \omega(g) &= \omega_{in}(g) + \omega_{out}(g) = 4 \\ B_v &= \{\beta_0, \beta_1, \beta_2, \beta_3\} \\ B_s &= \{0, 1, 2, 3\}\end{aligned}$$

To each bond corresponds a bond value β from bond value space B . $B(g)$ shall be denoted by the combination of bond structure B_s and bond values B_v . For any $g \in G$ the notation $B_s(g)$ will mean the set $\{b_j; j = 1, 2, \dots, \omega(g)\}$ and $B_v(g)$ will mean the set $\{\beta_j; 1, 2, \dots, \omega(g)\}$ where b_j means bond coordinate.

Configurations that satisfy a certain given constraint are known as regular. A generator with its bonds represents a structure that can be combined with other generators to form regular or partially regular configurations. A good analogy is

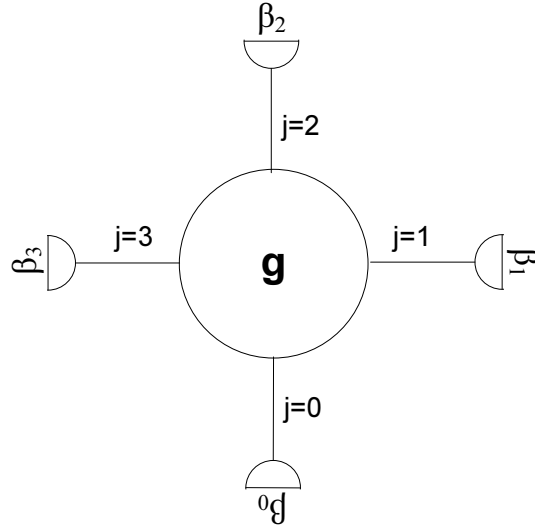


Figure 5.1. An example of a basic generator and its properties

the one that resembles the behavior of molecules which can be made of more atoms which are held together with their chemical bonds [102]. For each two generators the pair of bond values is either regular (true) or irregular (false). With this the local regularity is established that can be formalized with the structure formula in 5.1.

$$\bigwedge_{\langle k, kt \rangle} \rho[\beta_j(g_i), \beta_{j'}(g_{i'})] = TRUE \quad (5.1)$$

The algebraic component will express the rules of regularity whereas the optionally probabilistic one the variability. Pattern theory attempts to combine these two opposing themes. The aim of the next section will be to express the rules of the nuclear fuel cycle modelling language or better said the process structures in addition to the data structures formalized with meta-modelling. The possibility of presenting the variability aspect will be also discussed. Table 5.1 shows further

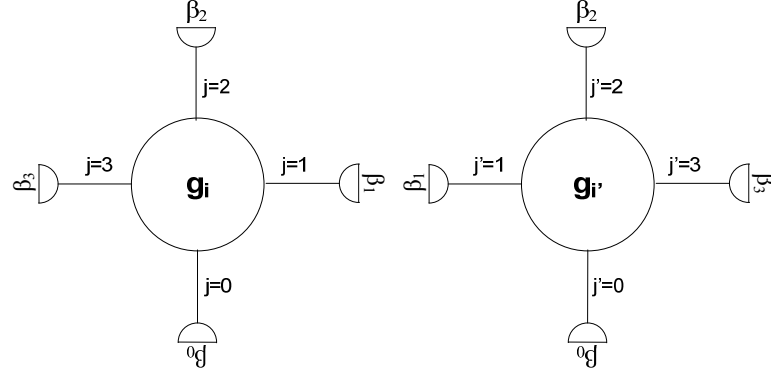


Figure 5.2. Diagrammatic representation of a generator g_i bonding to generator $g_{i'}$

	$\beta_{0,g'}$	$\beta_{1,g'}$	$\beta_{2,g'}$	$\beta_{3,g'}$
$\beta_{0,g}$	0	0	0	0
$\beta_{1,g}$	0	1	0	0
$\beta_{2,g}$	0	0	0	0
$\beta_{3,g}$	0	0	0	0

Table 5.1. Matrix showing bonds between two generators graphically presented in Figure 5.1. The truth value table where with 1 we denote the admissible connection between these two generators g and g' .

the way of representing the local constraints through a truth valued matrix.

5.2 Formalizing the Nuclear Fuel Cycle Model (NFCM)

In this section an attempt will be made to use configurations or sub-configurations to represent existing or potential weapons material acquisition paths modelled with NFCM. Local regularity of connected generators (modelling primitives) will be formalized in order for us to be able to check the consistency of modeled acquisition paths or infer inspection objectives. Both serve as examples of intended processing however many other algorithms are also possible.

To represent a nuclear fuel cycle process there are 8 major nuclear activities as listed below (i.e. Mining and Milling, Fuel Fabrication, Reactors etc.). Each of them can be represented with a generator connectable to other generators based on their structure (bonds) and bond value which in our case represents the nuclear material going in and out of these activities. The relation between different generators is based on the matching in and out-bond values. Each generator contains a structure and based on regularity rules possible combinations of nuclear activities in the fuel cycle can be represent as a regular configuration. These rules of regularity for this example application were extracted from the Physical Model (PM). PM is a document that defines each of the activities in the nuclear fuel cycle and the associated indicators [103, 104, 105, 106, 107].

5.3 Required level of formalism for NFCM using PT

When dealing with a model such as NFCM which represents the nuclear fuel cycle and can therefore be used to model an acquisition path there are two levels of granularity that can be considered for the formalization. The first is to take each activity of the nuclear fuel cycle as a generator and the second is to use the specific nuclear activity technologies as the atomic elements of this modelling language represented with generators. Technologies and materials used are represented with the modelling elements of the NFCM where an activity is represented as a large square whereas the technologies associates with the activity are shown as sub entities and are represented with smaller size squares. An example of the model and its elements is shown in Figure 5.3. For the purpose of applying algorithms such as analyzing potential acquisition paths the second granularity level was determined to be the appropriate one. The value assigned to the bond relating any two generators is based on the material that is produced by one nuclear activity and fed into the other. Based on the experiment made applying the lower level of granularity (generators as activities) difficulties were encountered to formalize the NFCM models. Difficulties met are generally characterized with one of more of the following issues:

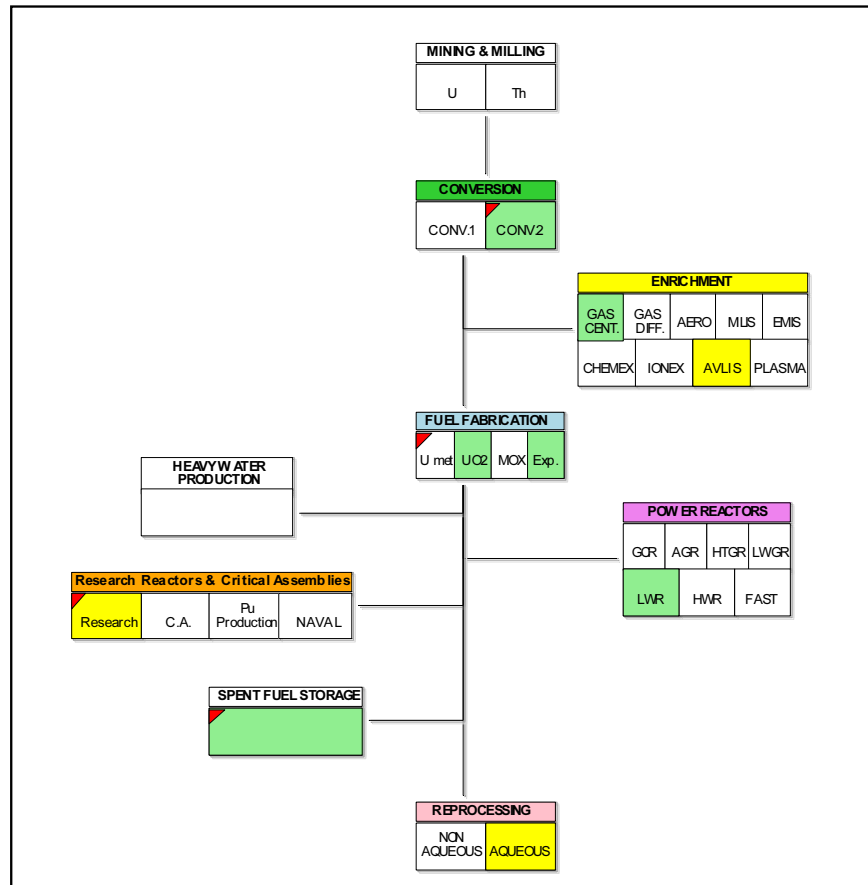


Figure 5.3. Nuclear Fuel Cycle Model represented with a modelling language implemented in ADOxx and based on the notation for describing State's Physical Model [1]

1. Each of the technologies representing the activity mean semantically different things. In some cases they represent distinct technologies and in others they are generalized. For example with the conversion activity it is often unambiguous and impossible to express semantic correctness as to which conversion phase is the MLIS enrichment related to.
2. Direction of the link between two activities. The aspect of bi-directional relation cannot be formalized with the approach shown. For instance in the example of the activities conversion and enrichment material going to enrichment returns for conversion into fuel elements or similar. It is not

possible to distinguish based on the bond value the direction modelled or in other cases the two directional relation.

To address these issues the following section will apply a higher level of formalism where modelling activities are actually classes of generators whereas generators represent technologies each activity is characterized with. In other word the technology associated to the nuclear activity is the atom of the modelling language. Technologies in the example model in Figure 5.3 are shown as smaller boxes within each nuclear activity element of modelling. Generators as elements of the generator class are identified with the name of the technology and are sequentially indexed from 0 to 30 (i.e. g_3, g_{23}).

As shown below all generators g_i are presented including the generator classes they belong to G^i . There are in total 31 generators. Classes of generators represent nuclear fuel cycle phases shown to contain generators representing the associated technology. Each class corresponds to a modelling element from the NFCM whereas the generators are the specific technology activities.

$$G^0 = \{\text{Mining and Milling}\}$$

$$G^1 = \{\text{Conv1, Conv2}\}$$

$$G^2 = \{\text{Gas cent, Gas diff, AERO, MLIS, EMIS, CHEMEX, IONEX, AVLIS, PLASMA}\}$$

$$G^3 = \{\text{Umet, UO2, MOX, EXP}\}$$

$$G^4 = \{\text{GCR, AGR, HTGR, LWGR, LWR, HWR, FAST}\}$$

$$G^5 = \{\text{Research Reactor, C.A., Pu Production, NAVAL}\}$$

$$G^6 = \{\text{Spent Fuel Storage}\}$$

$$G^7 = \{\text{Non-aqueous, aqueous}\}$$

$$G^8 = \{\text{Heavy Water}\}$$

Nuclear fuel cycle generator space G consists of the union of all generator spaces:

$$G = \bigcup_{\alpha \in A} G^\alpha$$

$$G = G^0 \cup G^1 \cup G^2 \cup G^3 \cup G^4 \cup G^5 \cup G^6 \cup G^7 \cup G^8$$

Where α is called generator index.

Generators can also have attributes which together with its structure (i.e. bonds) represent the properties of a generator [13]. Being able to also formalise attributes of generators has an important impact in addressing problem such as the one presented above under enumerated issue 2 discovered in the specific case of formalizing NFCM. All generators have common attributes in NFCM therefore $a \forall g \in G$ is the scale of the known or expected development which can be "production" or "research" represented with the notation colours "yellow", "green" on the model level. Example of attribute formalization is shown with expression 5.2.

$$a(g_i) = \text{"Research"} \quad (5.2)$$

The relation between the generators will be represented with the binary function ρ where the bonds that fit together are formalised. Matching bond values represented with β is the basis for defining the relation between each generator. Nuclear material going in and out of a nuclear activity is represented with β values of generators connected through bond coordinates (i, j) ; j is called bond coordinates for g_i . Next, all generators of the nuclear fuel cycle phases per modelling language NFCM will be formalised with the level of detail proposed. This is meant to demonstrate the application of pattern theory and offer a mathematical framework based on this theory for formalizing any other modelling language in order for the models to be processed through algorithms and mechanisms.

5.3.1 g_0 - Mining and Milling

Figure 5.4 shows on the left side generator g_0 is shown representing *Mining and Milling* and its structure consisting of two bonds β_0 and β_1 representing potential

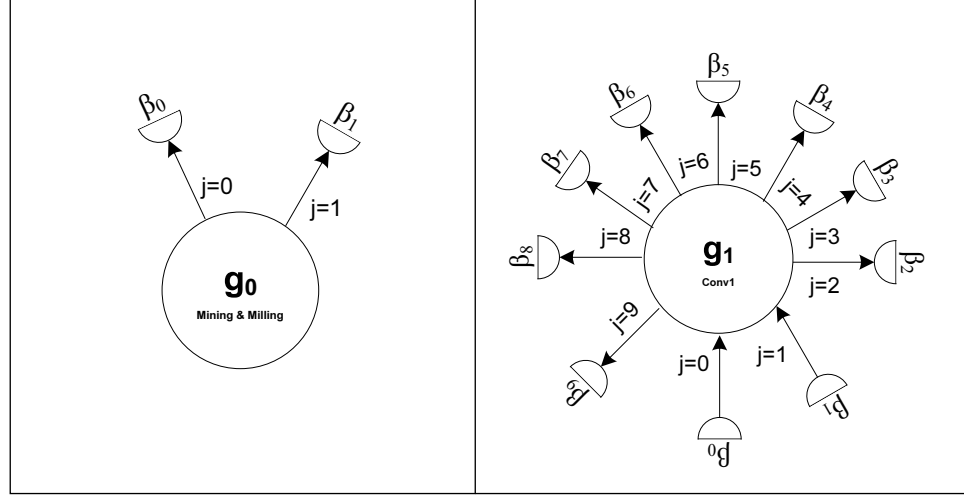


Figure 5.4. Generators g_0 representing *Mining and Milling* and g_1 representing the *Pre-Conversion (Conv.1)*

flow of Uranium or Thorium concentrate. On the right side is g_1 the generator representing *pre-conversion*. Two of its bonds link to g_0 depending on the feed material into the conversion process.

$$\begin{aligned}
 B_v &= \{\beta_0, \beta_1\} \\
 B_s &= \{0\} \\
 \omega_{in}(g_0) &= 0, \omega_{out}(g_0) = 2 \\
 \omega(g_0) &= \omega_{in}(g_0) + \omega_{out}(g_0) = 2
 \end{aligned}$$

This represents the relationship based on the use of UOC or UNO_3 (represented with β_0) or ThConc (represented with β_1) produced through mining and milling for the conversion 1 which converts the material to the form necessary for enrichment or fuel fabrication.

Definition of local regularity between two generators is expressed with the function ρ shown in 5.3 as proposed in [102].

$$\rho[\beta_j(g_i), \beta_j'(g_i')] = TRUE \quad (5.3)$$

To express the local regularity of the bond between g_0 and g_1 (conversion 1) where UOC is used as feed into the pre-conversion the local regularity can be formalised as shown in 5.4.

$$\rho[\beta_0(g_0), \beta_0(g_1)] = TRUE_{UOC} \quad (5.4)$$

For cases where Thorium concentrate is used as a feed material the locally regular bond can be formalised as shown in 5.5. ρ is equivalent to a relation and is called *bond value relation* [102].

$$\rho[\beta_1(g_0), \beta_0(g_1)] = TRUE_{ThConc} \quad (5.5)$$

The matching bonds of the two activities (technologies) representing local regularity for both cases can be also expressed with a matrix shown in the example based on the definition shown in 5.3 where j represents the and i is the generator identifier.

$$\rho : [(\beta ji), (\beta ji')] = 1 \quad (5.6)$$

$$\begin{array}{c} \beta_{01} \\ \beta_{11} \end{array} \left| \begin{array}{c|c} \beta_{00} & \beta_{10} \\ \hline 1 & 0 \\ 0 & 1 \end{array} \right|$$

Table 5.2. Matrix showing bonds between generators g_0 and g_1 . It formalizes regular bond connections based on the nuclear material and technology.

5.3.2 g_1 - Conversion 1 (pre-Conversion)

Conversion 1 also called pre-conversion includes all activities related to chemical transformations of natural nuclear material in order to provide feed material for isotope separation or reactor fuel fabrication [103].

$$\begin{aligned} B_s &= \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\} \\ B_v &= \{\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8, \beta_9\} \\ \omega_{in}(g_1) &= 2 \\ \omega_{out}(g_1) &= 8 \end{aligned}$$

Bond values assigned based on the nuclear material as shown in 5.7 and 5.8.

$$\beta_0 = UOC \vee UNO_3 \quad (5.7)$$

$$\begin{aligned} \beta_1 &= ThConc, \beta_2 = UF_6, \beta_3 = UCl_4, \beta_4 = ThO_2, \beta_5 = Thmet, \\ \beta_6 &= UF_4, \beta_7 = UO_3, \beta_8 = Umet, \beta_9 = UO_4 \end{aligned} \quad (5.8)$$

Each of the nuclear materials and the matching technologies are represented by bond values and the structure of generators. Next the bond relation between conversion 1 generator and the enrichment activities is formalised.

5.3.3 g_2 - Conversion 2 (post-Conversion)

Conversion 2, known also as "re-conversion" or "post-conversion", includes all chemical transformations subsequent to enrichment or reprocessing for the purpose of manufacturing reactor fuel elements [105].

$$\begin{aligned} B_s &= \{0, 1, 2, 3, 4, 5, 6, 7, 8\} \\ B_v &= \{\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8\} \\ \omega_{in}(g_2) &= 5 \\ \omega_{out}(g_2) &= 4 \end{aligned}$$

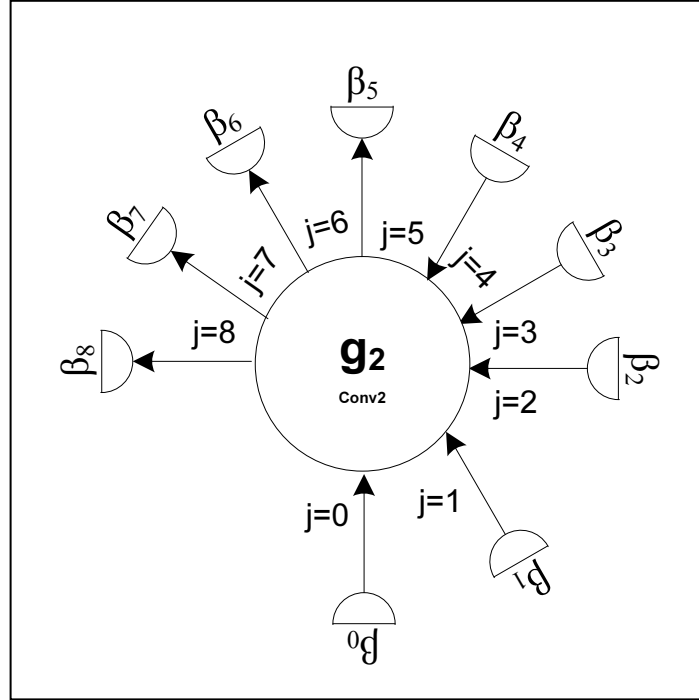


Figure 5.5. Generator representing Conversion 2 activity.

Input and output nuclear material is represented with in-bond and out-bond values respectively are shown in 5.9 and 5.10.

$$\beta_0 = P_{umet}, \beta_1 = PuNO_3, \beta_2 = UF_6e, \beta_3 = UCl_4e, \beta_4 = U_{met_{in}} \quad (5.9)$$

$$\beta_5 = UO_2, \beta_6 = PuO_2, \beta_7 = P_{umet}, \beta_8 = U_{met_{out}} \quad (5.10)$$

β_4 and β_8 both show bond values with Umet nuclear material. This examples shows them as two separate β indicating that Umet can be both input and output. Figure 5.5 shows the graphical formalism for this generator.

5.3.4 g_3 - Gas centrifuges

Gas centrifuges use the principle of centrifugal fields for the separation of gasses of different molecular weight. UF_6 gas is fed into mounted rotating cylinders [104]. Gas centrifuges is represented with the generator g_3 .

$g_3 = \text{Gas centrifuges}$

$$B_s = \{0, 1\}$$

$$B_v = \{\beta_0, \beta_1\}$$

$$\omega_{in}(g_3) = 1$$

$$\omega_{out}(g_3) = 1$$

Its two bonds are characterized with two β values shown in 5.3.4. β_0 represents the bond to the conversion 1 generator where UF_6 is used as feed material. Moreover, β_1 represents the product of the gas centrifuge enrichment which is subsequently processed in conversion 2.

$$\beta_0 = UF_6 \text{ and } \beta_1 = UF_6(enriched)$$

Use of gas centrifuges is represented with the generator g_3 . Use of gas centrifuges requires UF_6 feed material which is generated during conversion 1. The issue documented above as 1 can be resolved at this level of formalism since both directions of the material and therefore the bond between the two generators can be explicitly represented. This issue actually is non existent here since conversion 1 and conversion 2 represent two different generators. Graphical formalism is shown in figure 5.6 where g_3 along with other generators represents enrichment technology using UF_6 nuclear material. All of the generators shown in figure 5.6 have in common UF_6 as material that is fed and returned to the conversion process with higher abundance of U^{235} which is fissile depending on the enrichment level.

Following the graphical representation of the generator g_3 , expression in 5.11 restricts the configuration of generators by local constraints. Therefore a pair of bond values (β', β'') is regular if $\rho(\beta', \beta'') = TRUE$ or irregular if $\rho(\beta', \beta'') = FALSE$. The products space $B \times B$ of the bond value space B crossed with itself given a truth valued function represented with ρ where for the bond pair g_3 and g_1 local constraint is shown in 5.12.

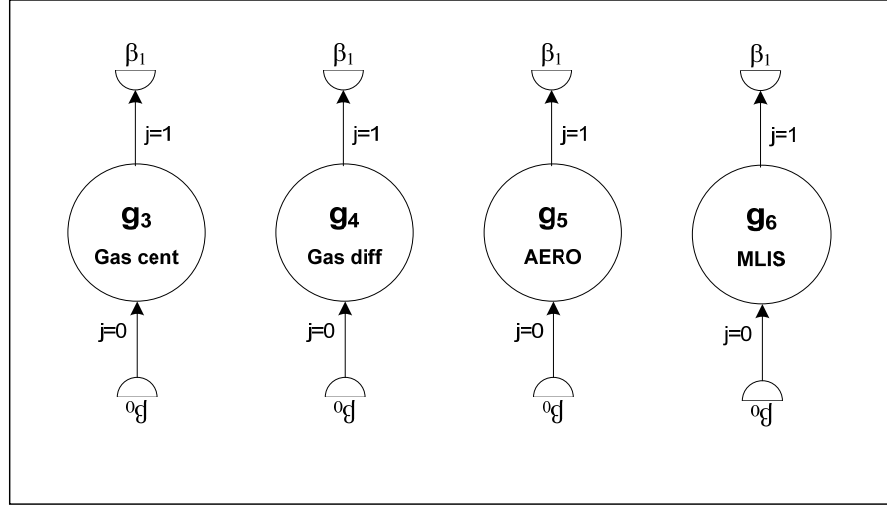


Figure 5.6. Generators of the *Enrichment* class. g_3, g_4, g_5 and g_6

$$\rho : B \times B \rightarrow \{TRUE, FALSE\} \quad (5.11)$$

or in this case the bond pair of g_3 and g_4 would be regular if

$$\rho[\beta_j(g_1), \beta_j'(g_3)] = TRUE \quad (5.12)$$

for g_3 or use of gas centrifuges for enrichment ρ is TRUE for:

$$\begin{aligned} \rho[\beta_2(conv.1), \beta_0(gasscent)] &= TRUE \\ \rho[\beta_1(gasscent), \beta_2(conv.2)] &= TRUE \end{aligned} \quad (5.13)$$

Expression in 5.13 shows the bond between the conversion activity where UF_6 is sent for enrichment and the same is returned for post-conversion or reconversion represented with the generator g_2 . The directionality is not an issues since for both feed materials and enrichment UF_6 are formalised with separate bonds.

5.3.5 g_4 - Gaseous Diffusion, g_5 - AERO and g_6 - MLIS

Generators presented here are also depicted with graphical formalism in figure 5.6. They are similar in the structure since they all use UF_6 as feed material to the enrichment process.

g_4 = Gaseous diffusion

$$B_s = \{0, 1\}$$

$$B_v = \{\beta_0, \beta_1\}$$

$$\omega_{in}(g_4) = 1$$

$$\omega_{out}(g_4) = 1$$

Gaseous diffusion is a process depending on the average velocity of a gas molecule at a given temperature which depends on the mass of the molecule. 235 isotope of UF_6 have a higher random molecular velocity than the 238 UF_6 molecules therefore provisioning for a stream of enriched 235 and depleted 235 isotopes [104].

$$\beta_0 = UF_6 \text{ and } \beta_1 = UF_6 \text{ (enriched)}$$

g_5 = AERO

$$B_s = \{0, 1\}$$

$$B_v = \{\beta_0, \beta_1\}$$

$$\omega_{in}(g_5) = 1$$

$$\omega_{out}(g_5) = 1$$

The aerodynamic enrichment processes UF_6 and light gas such as helium is compressed and then passed through where isotopic separation is achieved by generating high centrifugal force using curved-wall geometry [104].

$$\beta_0 = UF_6 \text{ and } \beta_1 = UF_6 \text{ (enriched)}$$

MLIS or the molecular laser enrichment represents a technique where molecules are excited when irradiated by laser light adjusted to the specific frequency. Due to mass differences between the isotopes 238 and 235 shifts in vibrational frequency allow for isotopic selectivity [104].

$$\begin{aligned}
g_6 &= MLIS \\
B_s &= \{0, 1\} \\
B_v &= \{\beta_0, \beta_1\} \\
\omega_{in}(g_6) &= 1 \\
\omega_{out}(g_6) &= 1
\end{aligned}$$

β_0 and β_1 similarly represent the bond values for this generator as shown below.

$$\beta_0 = UF_6 \text{ and } \beta_1 = UF_6 \text{ (enriched)}$$

Local regularity of all of the above generators and their bonds can be expressed with the definition provided in 5.3.

5.3.6 g_7 - EMIS

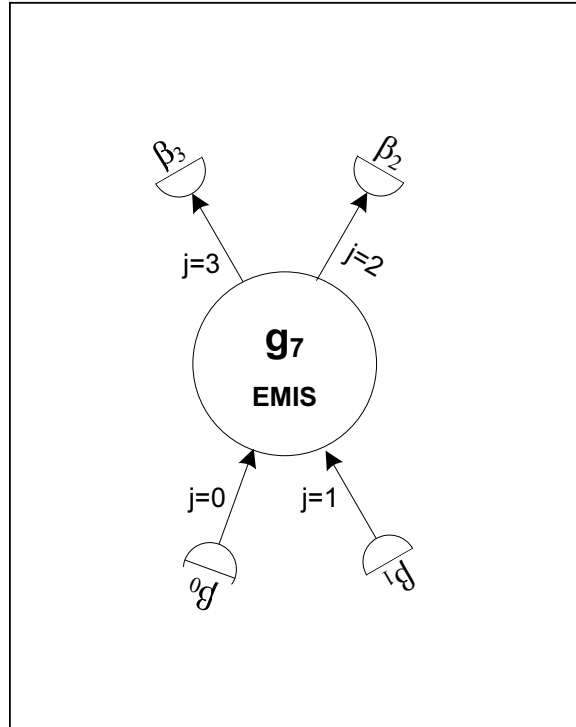


Figure 5.7. EMIS generator can use both UCl_4 and less desirably UF_6

	$\beta_{0,7}$	$\beta_{1,7}$	$\beta_{2,7}$	$\beta_{3,7}$
$\beta_{0,1}$	0	0	0	0
$\beta_{1,1}$	0	0	0	0
$\beta_{2,1}$	0	1	0	0
$\beta_{3,1}$	1	0	0	0
$\beta_{4,1}$	0	0	0	0
$\beta_{5,1}$	0	0	0	0
$\beta_{6,1}$	0	0	0	0
$\beta_{7,1}$	0	0	0	0
$\beta_{8,1}$	0	0	0	0
$\beta_{9,1}$	0	0	0	0

Table 5.3. Matrix showing bonds between generators g_7 and g_1 (conversion 1).

EMIS is characterized with the use of UCl_4 as feed material for the enrichment. There is an exception for this technology since UF_6 can also be used. The likelihood compared to UCl_4 is much smaller however. Figure 5.7 shows the generator for this enrichment technology.

Structure of this generator differs from the previous four shown above provisioning for both UF_6 and UCl_4 feed material.

$$\begin{aligned}
g_7 &= \text{EMIS} \\
B_s &= \{0, 1, 2, 3\} \\
B_v &= \{\beta_0, \beta_1, \beta_2, \beta_3\} \\
\omega_{in}(g_7) &= 2 \\
\omega_{out}(g_7) &= 2 \\
\beta_0 &= UCl_4, \beta_1 = UF_6, \beta_2 = UCl_4 \text{ enriched}, \beta_3 = UF_6 \text{ enriched}
\end{aligned}$$

Regularity for EMIS can be expressed with the function ρ shown in 5.16 or formalised with the use of a boolean matrix defined in 5.6. Example matrix is shown in table 5.3.

$$\rho : [\beta_j(g_i), \beta_{j'}(g_{i'})] \quad (5.14)$$

$$\rho : [\beta_3(g_1), \beta_0(g_7)] = TRUE \quad (5.15)$$

$$\rho : [\beta_2(g_1), \beta_1(g_7)] = TRUE \quad (5.16)$$

5.3.7 g_8 - CHEMEX and g_9 - IONEX

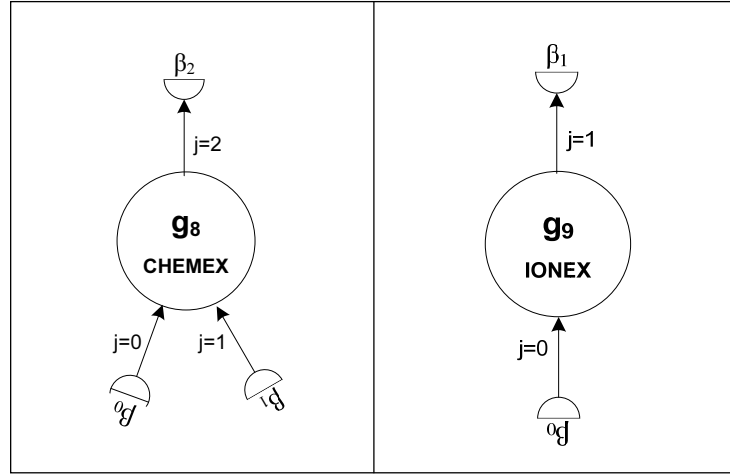


Figure 5.8. CHEMEX and IONEX generators used for UCl_4 enrichment

The CHEMEX short for Chemical Exchange uses kinetic and equilibrium differences in a valency dependent extraction system.

$$\begin{aligned}
 B_s &= \{0, 1, 2\} \\
 B_v &= \{\beta_0, \beta_1, \beta_2\} \\
 \omega_{in}(g_8) &= 2 \\
 \omega_{out}(g_8) &= 1 \\
 \beta_0 &= UCl_4, \beta_1 = UCl_3, \beta_2 = UCl_4 \text{ enriched}
 \end{aligned}$$

Generator g_8 (CHEMEX) has a bond with the generators g_1 and g_2 . Bonds of this generator as follows:

$$\rho : [\beta_3(g_1), \beta_0(g_8)] = TRUE \quad (5.17)$$

$$\rho : [\beta_3(g_1), \beta_0(g_8)] = TRUE \quad (5.18)$$

Furthermore, the bond between CHEMEX and Conv.2 (g_2) can be represented as:

$$\rho : [\beta_2(g_8), \beta_3(g_2)] = TRUE \quad (5.19)$$

Another enrichment process that uses uranium chloride UCl_4 is IONEX. It stands for Ion Exchange and it is called Asahi Chemical Exchange process (ACEP) developed by Asahi Chemical industries in Japan [104].

g_8 represents the IONEX generator with a structure $B_s = \{0, 1\}$. The corresponding bond values are $B_v = \{\beta_0, \beta_1\}$. It's in and out arity is defined as $\omega_{in}(g_9) = 1$ and $\omega_{out}(g_9) = 1$ with a total arity of 2. Values for the two bonds are defined as $\beta_0 = UCl_4$, $\beta_1 = UCl_4 enriched$.

Figure 5.8 shows both generators. Starting from left right g_8 CHEMEX and g_9 IONEX are shown.

5.3.8 g_{10} - AVLIS and g_{11} - PLASMA

These technologies are based on the principle of using Uranium in its metal form to achieve enrichment. Similarly with other generators its structure is shown below.

$$\begin{aligned} g_{10} &= \text{AVLIS} \\ B_s &= \{0, 1\} \\ B_v &= \{\beta_0, \beta_1\} \\ \omega_{in}(g_{10}) &= 1 \\ \omega_{out}(g_{10}) &= 1 \\ \beta_0 &= Umet, \beta_1 = Umet \text{ enriched} \end{aligned}$$

AVLIS that stands for Atomic Vapour Laser Isotope Separation has a bond with the generators g_1 and g_2 . With β_0 the bond value represented is Umet as input to the process and β_1 enriched Umet as output of the process. The truth function for both bonds is provided in 5.20 and 5.21.

The bond represented by the Umet leaving conversion $1(g_1)$ is defined as:

$$\rho : [\beta_8(g_1), \beta_0(g_{10})] = TRUE \quad (5.20)$$

and subsequently enriched Umet going to conversion 2 (g_2)

$$\rho : [\beta_1(g_{10}), \beta_4(g_2)] = TRUE \quad (5.21)$$

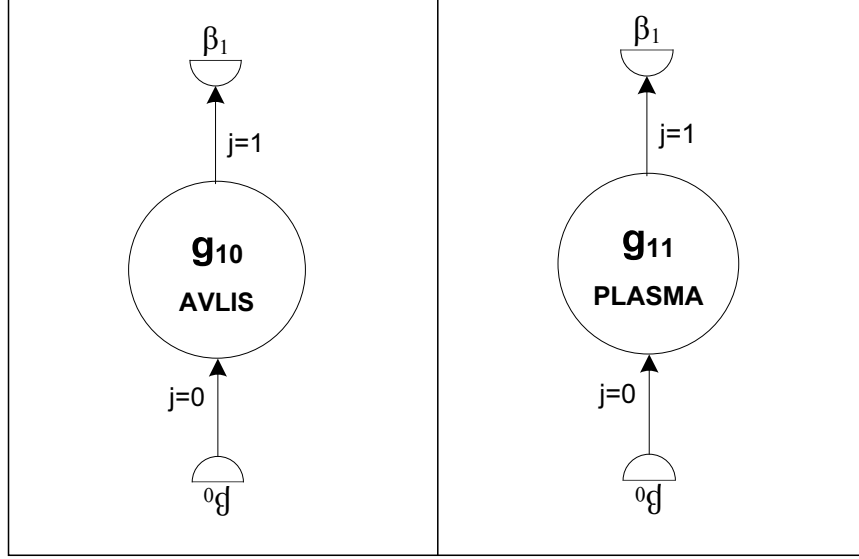


Figure 5.9. AVLIS and PLASMA generators representing technologies for enrichment of Umet.

The second generator in the group of generators that use Umet as source material for enrichment is PLASMA. Known as the plasma separation process (PSP). The process includes forming a plasma containing mixture of 235 and 235 U isotopes ions. The created plasma is confined by a strong permanent magnetic field causing circular motion of the ions. The frequency of the circular motion of an ion depends on its mass and the intensity of the magnetic field. Since frequencies of the two isotopes differ slightly allowing for selective collection.

$$\begin{aligned}
 g_{11} &= \text{PLASMA} \\
 B_s &= \{0, 1\} \\
 B_v &= \{\beta_0, \beta_1\} \\
 \omega_{in}(g_{10}) &= 1 \\
 \omega_{out}(g_{10}) &= 1 \\
 \beta_0 &= \text{Umet}, \beta_1 = \text{Umet enriched}
 \end{aligned}$$

Also in the case of PLASMAThe bond represented by the Umet leaving conversion 1(g_1) is defined as:

$$\rho : [\beta_8(g_1), \beta_0(g_{11})] = TRUE \quad (5.22)$$

and subsequently enriched Umet going to conversion 2 (g_2)

$$\rho : [\beta_1(g_{11}), \beta_4(g_2)] = TRUE \quad (5.23)$$

5.3.9 g_{12} - Umet Fuel Fabrication

This sections introduces the first generator in the line of generators formalising modelling elements for representing fuel fabrication technologies.

$$\begin{aligned} g_{12} &= \text{Umet Fuel Fabrication} \\ B_s &= \{0, 1\} \\ B_v &= \{\beta_0, \beta_1\} \\ \omega_{in}(g_{12}) &= 1 \\ \omega_{out}(g_{12}) &= 1 \\ \beta_0 &= \text{Umet}, \beta_1 = \text{Umet fuel} \end{aligned}$$

The above definition of this generator and all other fuel fabrication generators are also graphically presented in figure 5.10.

If we were to represent the bond between g_{12} and conv.2 it would be expressed with the following:

$$\rho : [\beta_8(g_2), \beta_0(g_{12})] = TRUE \quad (5.24)$$

and subsequently Umet fuel going to reactors or critical assemblies the bond can be presented as follows where an example of a bond to the generator representing GCR reactors is shown.

$$\rho : [\beta_1(g_{12}), \beta_0(g_{16})] = TRUE \quad (5.25)$$

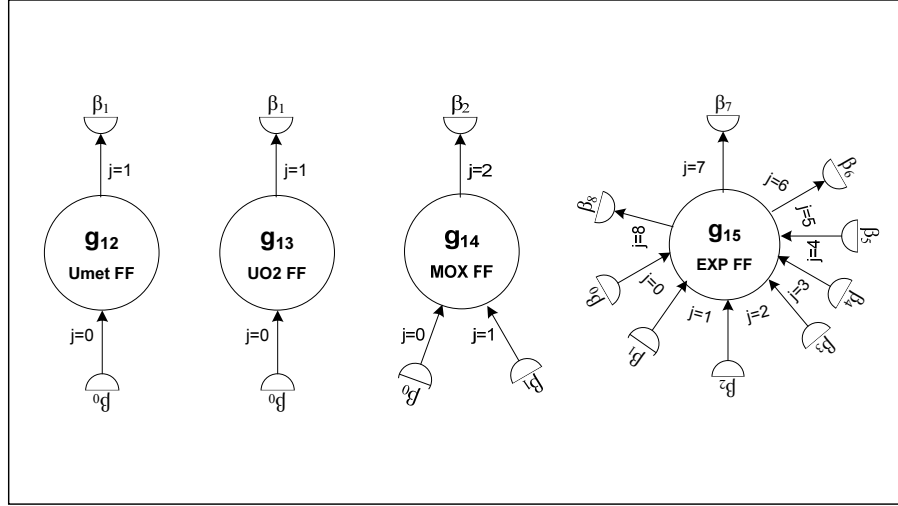


Figure 5.10. Generators of the *Fuel Fabrication* class consisting of g_{12} , g_{13} , g_{14} and g_{15} .

5.3.10 g_{13} - UO_2 Fuel Fabrication

$g_{13} = UO_2$ Fuel Fabrication

$$B_s = \{0, 1\}$$

$$B_v = \{\beta_0, \beta_1\}$$

$$\omega_{in}(g_{13}) = 1$$

$$\omega_{out}(g_{13}) = 1$$

$$\beta_0 = UO_2, \beta_1 = UO_2 \text{ fuel}$$

5.3.11 g_{14} - MOX Fuel Fabrication

$g_{14} = \text{MOX Fuel Fabrication}$

$$B_s = \{0, 1, 2\}$$

$$B_v = \{\beta_0, \beta_1, \beta_2\}$$

$$\omega_{in}(g_{14}) = 2$$

$$\omega_{out}(g_{14}) = 1$$

$$\beta_0 = PuO_2, \beta_1 = P_{umet}, \beta_2 = \text{MOX fuel}$$

	$\beta_{0,15}$	$\beta_{1,15}$	$\beta_{2,15}$	$\beta_{3,15}$	$\beta_{4,15}$	$\beta_{5,15}$	$\beta_{6,15}$	$\beta_{7,15}$	$\beta_{8,15}$	$\beta_{9,15}$	$\beta_{10,15}$	$\beta_{11,15}$
β_{01}	0	0	0	0	0	0	0	0	0	0	0	0
β_{11}	0	0	0	0	0	0	0	0	0	0	0	0
β_{21}	0	0	0	0	0	0	0	0	0	0	0	0
β_{31}	0	0	0	0	0	0	0	0	0	0	0	0
β_{41}	0	0	0	0	1	0	0	0	0	0	0	0
β_{51}	0	0	0	0	0	1	0	0	0	0	0	0
β_{61}	0	0	0	0	0	0	0	0	0	0	0	0
β_{71}	0	0	0	0	0	0	0	0	0	0	0	0
β_{81}	1	0	0	0	0	0	0	0	0	0	0	0
β_{91}	0	1	0	0	0	0	0	0	0	0	0	0

Table 5.4. Matrix showing bonds between generators g_1 conversion 1 and g_{15} experimental fuel fabrication.

5.3.12 g_{15} - EXP Fuel Fabrication

g_{15} = Experimental Fuel Fabrication

$$B_s = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11\}$$

$$B_v = \{\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8, \beta_9, \beta_{10}, \beta_{11}\}$$

$$\omega_{in}(g_{15}) = 6$$

$$\omega_{out}(g_{15}) = 6$$

In-bond values and out-bond values are defined as :

$$\begin{aligned} \beta_0 &= Umet, \beta_1 = UO_2, \beta_2 = PuO_2, \beta_3 = Pumet, \beta_4 = ThO_2, \\ \beta_5 &= Thmet, \beta_6 = PuO_2fuel, \beta_7 = Pumetfuel, \beta_8 = Thmetfuel, \beta_9 = ThO_2fuel, \\ \beta_{10} &= Umetfuel, \beta_{11} = UO_2fuel \end{aligned} \quad (5.26)$$

In order to represent the bond between the generators g_1 and the experimental fuel fabrication g_{15} a binary matrix is presented in table 5.4.

$$\rho[\beta_j(g_1), \beta_{j'}(g_{15})] \quad (5.27)$$

	$\beta_{0,15}$	$\beta_{1,15}$	$\beta_{2,15}$	$\beta_{3,15}$	$\beta_{4,15}$	$\beta_{5,15}$	$\beta_{6,15}$	$\beta_{7,15}$	$\beta_{8,15}$
β_{02}	0	0	0	0	0	0	0	0	0
β_{12}	0	0	0	0	0	0	0	0	0
β_{22}	0	0	0	0	0	0	0	0	0
β_{32}	0	0	0	0	0	0	0	0	0
β_{42}	0	0	0	0	0	0	0	0	0
β_{52}	0	1	0	0	0	0	0	0	0
β_{62}	0	0	1	0	0	0	0	0	0
β_{72}	0	0	0	1	0	0	0	0	0
β_{82}	1	0	0	0	0	0	0	0	0

Table 5.5. Matrix showing bonds between generators g_2 conversion 2 and g_{15} experimental fuel fabrication.

Similarly the bond between the generators g_2 conversion 2 and the experimental fuel fabrication can be shown with a binary matrix in table 5.5 based on the following definition:

$$\rho : [\beta_j(g_2), \beta_{j'}(g_{15})] \quad (5.28)$$

5.3.13 g_{16} to g_{22} - Reactors

This section includes all reactors are represented as generators of the class G^4 . The structure of the generators varies depending on the different types of fuels that can be used in a particular type of reactor. The in-bonds vary however there is commonly only one out-bond which represents the burned fuel headed to the spent fuel pond or separate storage.

The first presented is GCR type of reactor that can use Umet and ThO_2 . Burned fuel out of this reactor is represented with β_2 .

$$\begin{aligned}
 g_{16} &= \text{GCR} \\
 B_s &= \{0, 1, 2\} \\
 B_v &= \{\beta_0, \beta_1, \beta_2\} \\
 \omega_{in}(g_{16}) &= 2 \\
 \omega_{out}(g_{16}) &= 1
 \end{aligned}$$

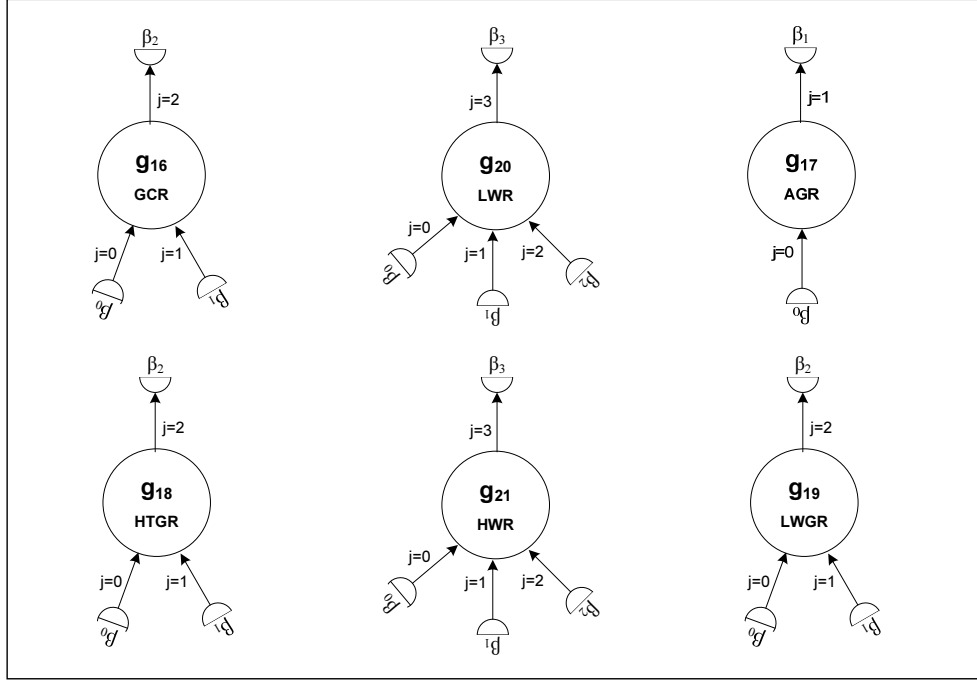


Figure 5.11. Generators representing all reactors other than FAST and research reactors.

$$\beta_0 = \text{Umet fuel}, \beta_1 = \text{ThO}_2 \text{ fuel}, \beta_2 = \text{GCR spent fuel}$$

Figure 5.11 shows all the generators of the Reactor class. FAST reactor is not shown in the figure and will be presented separately as it is used as an example due to its generator structure complexity. Here, also research reactors and critical assemblies are not shown as they are a part of another class G^5 .

Next are AGR, HTGR type of reactors that can use UO_2 and ThO_2 . Spent fuel out of this reactor is represented respectively with β_2 and β_2 .

$$g_{17} = \text{AGR}$$

$$B_s = \{0, 1\}$$

$$B_v = \{\beta_0, \beta_1\}$$

$$\omega_{in}(g_{17}) = 1$$

$$\omega_{out}(g_{17}) = 1$$

$$\beta_0 = \text{UO}_2 \text{ fuel}, \beta_1 = \text{AGR spent fuel}$$

$$\begin{aligned}
g_{18} &= \text{HTGR} \\
B_s &= \{0, 1, 2\} \\
B_v &= \{\beta_0, \beta_1, \beta_2\} \\
\omega_{in}(g_{18}) &= 2 \\
\omega_{out}(g_{18}) &= 1 \\
\beta_0 &= \text{UO}_2 \text{ fuel}, \beta_1 = \text{ThO}_2 \text{ fuel}, \beta_2 = \text{HTGR spent fuel}
\end{aligned}$$

Reactors that are moderated with water, so called Light Water Reactors are defined below.

$$\begin{aligned}
g_{19} &= \text{LWGR} \\
B_s &= \{0, 1, 2\} \\
B_v &= \{\beta_0, \beta_1, \beta_1\} \\
\omega_{in}(g_{19}) &= 2 \\
\omega_{out}(g_{19}) &= 1 \\
\beta_0 &= \text{Umet fuel}, \beta_1 = \text{UO}_2 \text{ fuel}, \beta_2 = \text{LWGR spent fuel}
\end{aligned}$$

LWR reactors represent the most common type. They can also used mixed oxide fuel known as MOX.

$$\begin{aligned}
g_{20} &= \text{LWR} \\
B_s &= \{0, 1, 2, 3\} \\
B_v &= \{\beta_0, \beta_1, \beta_2, \beta_3\} \\
\omega_{in}(g_{20}) &= 3 \\
\omega_{out}(g_{20}) &= 1 \\
\beta_0 &= \text{UO}_2 \text{ fuel}, \beta_1 = \text{ThO}_2 \text{ fuel}, \beta_2 = \text{MOX fuel}, \beta_3 = \text{LWR spent fuel}
\end{aligned}$$

The next type of generator is one of the few that uses Heavy Water as moderant/coolant. Since light water reactor necessitates enrichment of fuel this can be overcome with use of heavy water and natural uranium or slightly enriched fuel [106].

$$\begin{aligned}
g_{21} &= \text{HWR} \\
B_s &= \{0, 1, 2, 3\} \\
B_v &= \{\beta_0, \beta_1, \beta_2, \beta_3\}
\end{aligned}$$

$$\omega_{in}(g_{21}) = 3$$

$$\omega_{out}(g_{21}) = 1$$

$$\beta_0 = UO_2 \text{ fuel}, \beta_1 = \text{Umet fuel}, \beta_2 = \text{Heavy Water}, \beta_3 = \text{HWR spent fuel}$$

5.3.14 g_{22} - FAST Reactor

Fast reactors are characterized with high-energy neutrons causing most fissions. No moderation is required and they use liquid metal as coolant. It requires fuel of higher enrichment due to reduced fission cross-section at the higher neutron energies [106].

$$g_{22} = \text{FAST}$$

$$B_s = \{0, 1, 2, 3, 4, 5\}$$

$$B_v = \{\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5\}$$

$$\omega_{in}(g_{22}) = 5$$

$$\omega_{out}(g_{22}) = 1$$

$$\begin{aligned} \beta_0 &= UO_2 \text{ fuel}, \beta_1 = Th \text{ met fuel}, \beta_2 = U \text{ met fuel}, \beta_3 = MOX \text{ fuel}, \\ \beta_4 &= Pu \text{ met fuel}, \beta_5 = PuO_2 \text{ fuel}, \beta_6 = FAST \text{ spent fuel} \end{aligned} \quad (5.29)$$

Figure 5.12 shows the generator representing the FAST reactors. It's in-arity is 5 and as most other reactors the out-arity was defined to be 1 representing the fuel spent.

To exemplify the local regularity of the bonds between a reactor and the preceding fuel fabrication activity FAST reactor bonds to fuel fabrication are formalised using the expression 5.3. Furthermore, the formalisation is expressed with a matrix shown in table. Bonds between g_{22} and generators g_{13} , g_{14} and g_{15} are shown.

In the case where UO_2 fuel is used in FAST reactors the bond between UO_2 fuel fabrication and reactor would be formalised as shown in 5.30.

$$\rho : [\beta_1(g_{13}), \beta_0(g_{22})] = TRUE \quad (5.30)$$

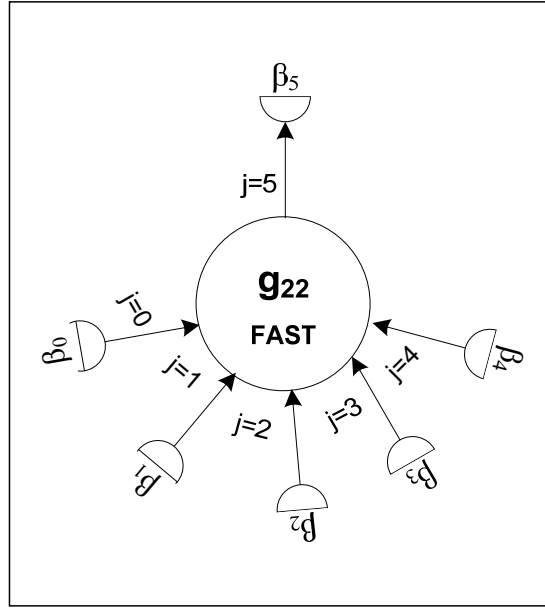


Figure 5.12. FAST reactor represented by the generator g_{22} .

The bond between fabrication of MOX fuel also used in a FAST reactor will be similarly expressed with 5.31.

$$\rho : [\beta_2(g_{14}), \beta_3(g_{22})] = TRUE \quad (5.31)$$

Representing more complex relations between bonds such as the example of FAST reactor and the fuel fabrication of experimental fuel would be presented with a matrix as shown in table 5.6.

5.3.15 g_{23} - Research Reactor

Research Reactors cover a broad range of reactors which generally speaking are used for purposes other than energy [106].

Research reactors are represented by the generator g_{23} and are characteristic with having a great number of in-bond as a result of broad range of nuclear fuels that are used for research.

	$\beta_{0,22}$	$\beta_{1,22}$	$\beta_{2,22}$	$\beta_{3,22}$	$\beta_{4,22}$	$\beta_{5,22}$
$\beta_{0,15}$	0	0	0	0	0	0
$\beta_{1,15}$	0	0	0	0	0	0
$\beta_{2,15}$	0	0	0	0	0	0
$\beta_{3,15}$	0	0	0	0	0	0
$\beta_{4,15}$	0	0	0	0	0	0
$\beta_{5,15}$	0	0	0	0	0	0
$\beta_{6,15}$	0	0	0	0	0	1
$\beta_{7,15}$	0	0	0	0	1	0
$\beta_{8,15}$	0	1	0	0	0	0

Table 5.6. Matrix showing bonds between generators g_{15} experimental fuel fabrication and g_{22} FAST reactor.

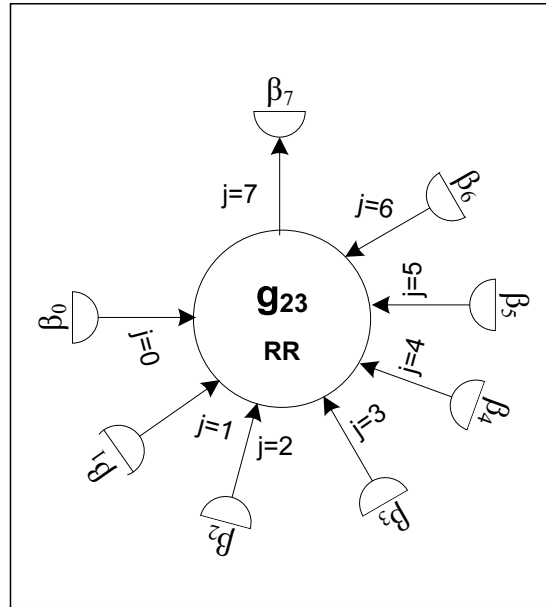


Figure 5.13. Research Reactor formalised as generator g_{23} .

$$\begin{aligned}
 g_{23} &= \text{RR} \\
 B_s &= \{0, 1, 2, 3, 4, 5, 6, 7\} \\
 B_v &= \{\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7\} \\
 \omega_{in}(g_{23}) &= 6 \\
 \omega_{out}(g_{23}) &= 1
 \end{aligned}$$

$$\begin{aligned}\beta_0 &= UO_2fuel, \beta_1 = Thmetfuel, \beta_2 = ThO_2fuel, \beta_3 = Umetfuel, \\ \beta_4 &= MOXfuel, \beta_5 = Pumetfuel, \beta_6 = PuO_2fuel, \beta_7 = spentfuel\end{aligned}\quad (5.32)$$

Bonds and the bond values shown for Research Reactors identify that this activity relates to all type of fuel coming from fuel fabrication. This can be also formalised here however was not included for brevity.

5.3.16 g_{24} - Critical Assembly

Critical Assemblies as it was the case with RR are used for purposes other than energy production [106].

CAs are represented by the generator g_{24} and has identical generator structure with the research reactors (g_{23}) shown in Figure 5.13 and described above.

5.3.17 g_{25} - Pu Production and g_{26} - Naval Reactor

Generators representing Pu Production or g_{25} is different from other reactors described. NFCM modelling language adopted the notation suggested by Liu et al where seems to be an inconsistency in this class of generators. Other reactors are represented by their type based on the technology whereas *Pu Production* represents a generator that more represents a purpose. Pu Production will be defined as a generator which has bonds to all generators of the fuel fabrication generator class presented below.

$$\begin{aligned}g_{25} &= \text{Pu Production} \\ B_s &= \{b_j; j = 1, 2, \dots, \omega(g_{12-15})\} \\ B_v &= \{\beta_j; 1, 2, \dots, \omega(g_{12-15})\}\end{aligned}$$

Although not also documented in detail in the physical model of reactors another generator left in the class of reactors is g_{26} .

$$\begin{aligned}g_{26} &= \text{Naval Reactor} \\ B_s &= \{0, 1, 2\}\end{aligned}$$

$$B_v = \{\beta_0, \beta_1, \beta_2\}$$

$$\omega_{in}(g_{26}) = 2$$

$$\omega_{out}(g_{26}) = 1$$

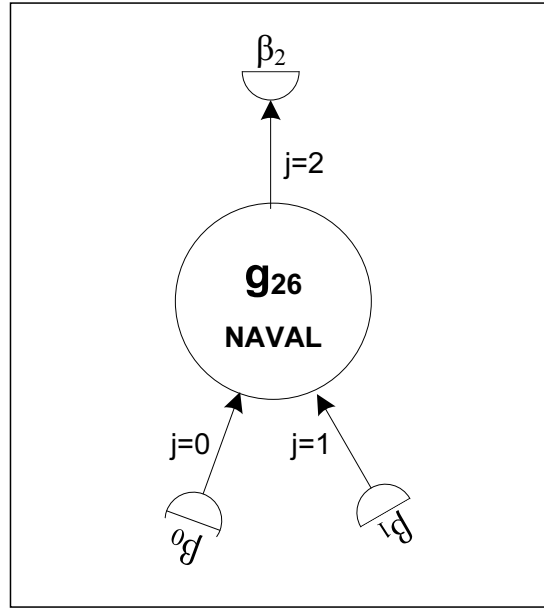


Figure 5.14. Naval reactor represented by the generator g_{26} containing of two in-bonds and one out-bond denoted with bond values β_0, β_1 and β_2 .

5.3.18 g_{27} - Spent Fuel Storage

This activity relates to the management of fuel which starts with the discharge from a reactors ending with permanent disposal.

Irradiated fuel from the reactors is sent to a storage are which is represented in NFCM with the modelling element Spent Fuel Storage. To formalise this element it is represented with generator g_{27} . Relation of this generator can exist between on the premises that all spent fuel is sent to the storage therefore bond relation is based on the bond relation between all out-bonds of the reactor class and the single spent fuel generator in its class. Furthermore, there is a relation between the spent fuel generator and the reprocessing generators defined further down.

A generalized form of expressing the relation between this generator and all reactors could be expressed as

$$\begin{aligned} g_{27} &= \text{Spent Fuel Storage} \\ B_s &= \{b_j; j = 1, 2, \dots, \omega(g_{16-26})\} \\ B_v &= \{\beta_j; 1, 2, \dots, \omega(g_{16-26})\} \end{aligned}$$

A more explicit form of expressing all the bond relations based on all types of spent fuel sent from reactors to the spent fuel storage is shown in figure 5.15.

$$\begin{aligned} g_{27} &= \text{Spent Fuel Storage} \\ B_s &= \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11\} \\ B_v &= \{\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8, \beta_9, \beta_{10}, \beta_{11}\} \\ \omega_{in}(g_{27}) &= 10 \\ \omega_{out}(g_{27}) &= 1 \end{aligned}$$

Where bond values represent spent fuel from all types of reactors as shown in 5.33.

$$\begin{aligned} \beta_0 &= GCRspentfuel, \beta_1 = AGRspentfuel, \beta_2 = HTGspentfuel, \\ \beta_3 &= LGERSpentfuel, \beta_4 = LWRspentfuel, \beta_5 = HWRspentfuel, \\ \beta_6 &= FASTspentfuel, \beta_7 = RRspsentfuel, \beta_8 = RRspsentfuel, \\ \beta_9 &= CAspsentfuel, \beta_{10} = Navalspentfuel, \beta_{11} = Allspentfuel \quad (5.33) \end{aligned}$$

5.3.19 g_{28} - Non-aqueous and g_{29} Aqueous Reprocessing

Reprocessing of irradiated nuclear fuel is mainly aimed at the recovery of residual or bred fissile material for further use (i.e. fuel fabrication). The further use of the retrieved fissile material can be in power generation, research as well as nuclear weapons related activities. Specific recovered material can find use in medicine and related research. A number of routes for extracting uranium and plutonium were explored based on aqueous and non-aqueous separation methods. Commonly used aqueous methods are Precipitation, Ion exchange and Solvent extraction [107].

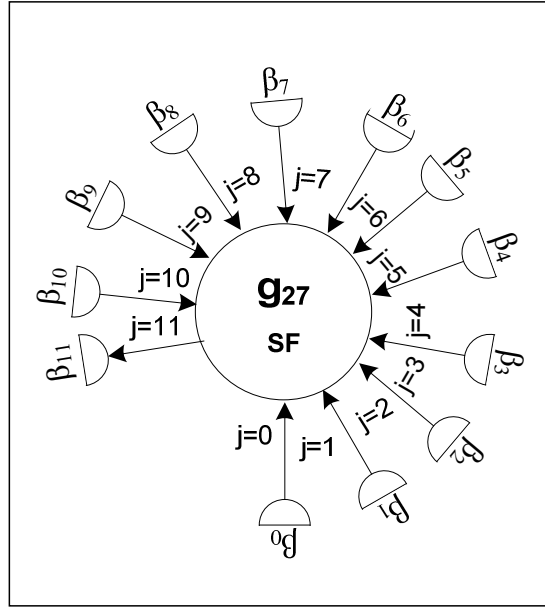


Figure 5.15. Spent fuel storage generator represented with g_{27} containing in-bonds relation to all reactors and two out-bond denoted with bond values β_{11} and β_{12} .

Figure 5.16 shows the two generators representing the reprocessing generator class. g_{28} is the generator formalising reprocessing based on aqueous methods whereas g_{29} is the generator for non-aqueous reprocessing. In both cases the in-bonds are for receiving any type of fuel spent fuel from storage facilities or reactors. The out-bonds are represented with relation bond values consisting of uranyl nitrate UNO_3 and Pu nitrate $PuNO_3$ extracted which can be used in Conversion 1 (g_1) and Conversion 2 (g_2). Structures of both methods are shown below.

$$\begin{aligned}
 g_{28} &= \text{Aqueous} \\
 B_s &= \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11\} \\
 B_v &= \{\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8, \beta_9, \beta_{10}, \beta_{11}, \beta_{12}\} \\
 \omega_{in}(g_{28}) &= 11 \\
 \omega_{out}(g_{28}) &= 2 \\
 g_{29} &= \text{Non-Aqueous}
 \end{aligned}$$

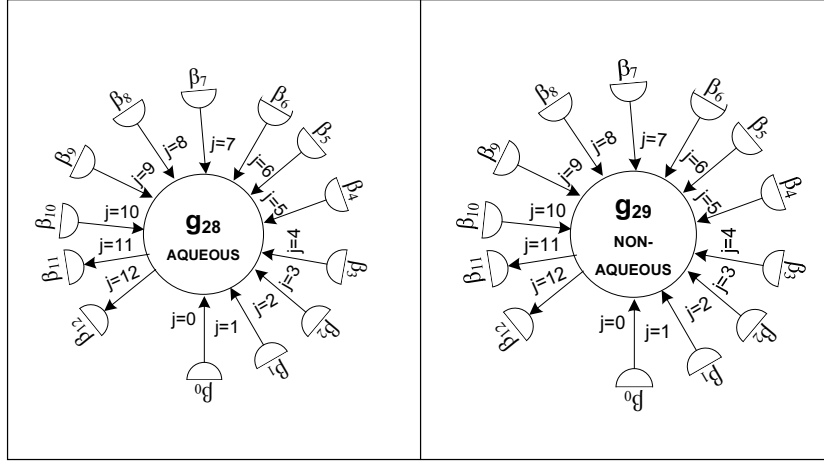


Figure 5.16. Aqueous and non-aqueous generators of the reprocessing class.

$$\begin{aligned}
 B_s &= \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11\} \\
 B_v &= \{\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8, \beta_9, \beta_{10}, \beta_{11}, \beta_{12}\} \\
 \omega_{in}(g_{29}) &= 11 \\
 \omega_{out}(g_{29}) &= 2
 \end{aligned}$$

for both generators the bond values are assigned are shown below in 5.34.

$$\begin{aligned}
 \beta_0 &= GCRspentfuel, \beta_1 = AGRspentfuel, \beta_2 = HTGspentfuel, \\
 \beta_3 &= LGERspentfuel, \beta_4 = LWRspentfuel, \beta_5 = HWRspentfuel, \\
 \beta_6 &= FASTspentfuel, \beta_7 = RRsspentfuel, \beta_8 = RRsspentfuel, \\
 \beta_9 &= CAspentfuel, \beta_{10} = Navalspentfuel, \\
 \beta_{11} &= PuNO_3, \beta_{12} = UNO_3 \quad (5.34)
 \end{aligned}$$

Reprocessing may in some cases be sought as a part of waste management for nuclear fuel. As a part of waste management process separating parts of the irradiated fuel into separate components allowing for better and more appropriate treatment based on individual characteristics [107].

5.3.20 g_{30} - Deuterium/Heavy Water Production

Heavy water is used as a moderator HWR reactors described above. Production is obtained with the enrichment of Deuterium (D) found mainly in natural water with the form HDO. The reason this activity appears in the physical model is since it is required for the operation of a heavy water reactor (HWR) in large quantities and as a possible light element used in the fabrication of nuclear weapons.

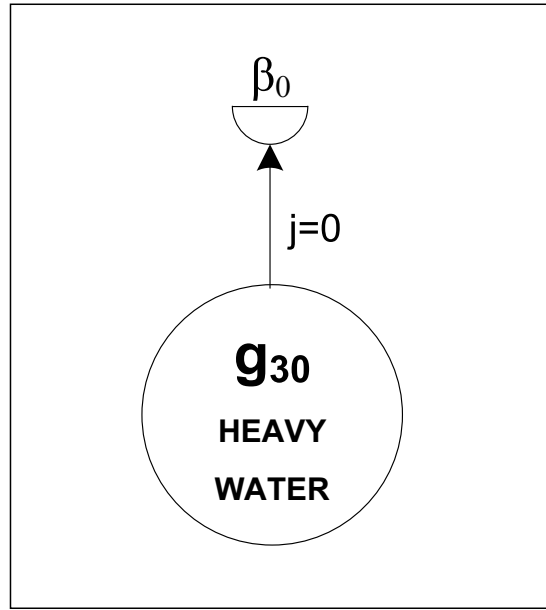


Figure 5.17. Generator representing Heavy Water Production D_2O .

This modelling element has an inarity of zero and a total arity of 1 represented with the bond value $\beta_0 = D_2O$ which is a must for HWR reactors represented by $\beta_2(g_{21})$.

g_{30} = Heavy Water Production

$$B_s = \{0\}$$

$$B_v = \{\beta_0\}$$

$$\omega_{in}(g_{30}) = 0$$

$$\omega_{out}(g_{30}) = 1$$

5.4 Acquisition path configuration

Generators creating the generator space G can be glued together and the bonds determine which combination can hold. This resembles the behaviours of atoms which here would be generators that are connected into molecules or in this case configurations.

The next step is to form a configuration of generators that can bond. In the example here representing the nuclear fuel cycle model the generators representing nuclear activities are the atoms that need to be combined in a configuration. Acquisition path using the generators formalised in the previous section can be represented as a combination of bonding nuclear activity generators into potential routes of acquiring a nuclear weapon.

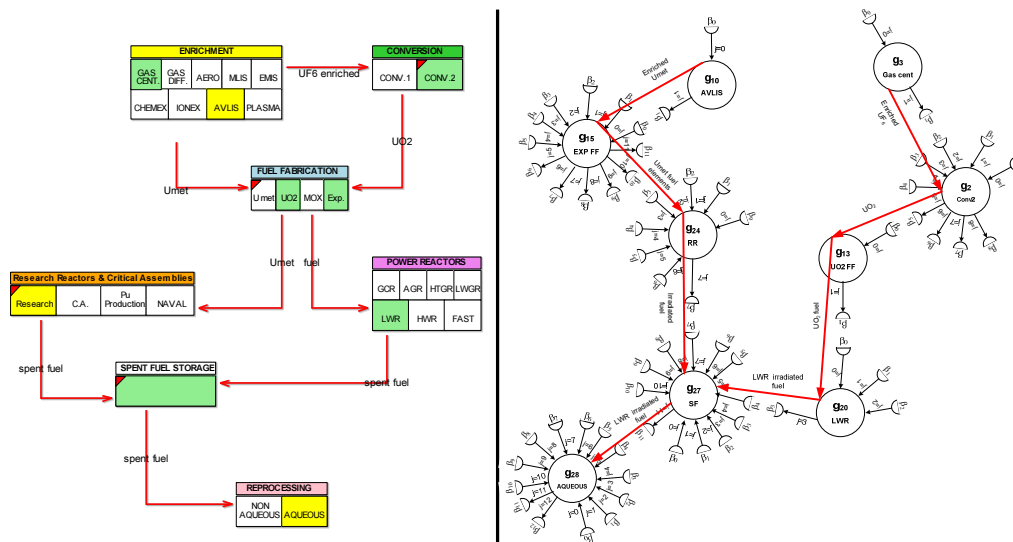


Figure 5.18. Representation of the NFCM model shown above with the PT formalism. Internal bonds make up the configuration of the physical model for the fictitious state Ruritania. Panel on the right shows the generators used to represent the activities shown with the NFCM model. The state enriches U and fabricates UO_2 fuel which is used for a LWR reactor. Furthermore, the state has research activities for U metal enrichment using AVLIS. The enriched U metal is used for fabricating fuel elements that are irradiated in a research reactor. In the presence of a Spent Fuel Storage at a research scale some of the irradiated fuel is reprocessed using the aqueous method.

Bonds denoted by $b_1, b_2, \dots, b_\omega$ represent generator coordinates which build the configuration architecture of the model. σ called the *connector* represents a graph of sites that are connected with their bonds. An example *configuration* for Ruritania can be diagrammatically presented as depicted in figure 5.18 or can be expressed as in 5.35. The configuration codifying the instance of the NFCM on the left panel consists of 9 generators differently connected to each other through their internal bonds. Generators g_{20} and g_{24} both bond to the generator g_{27} . The same can also be diagrammatically expressed by having two identical copies of the generator g_{27} which can then be kept separately by using identifying marks as parts of the attributes. The same is true should there be a need to use more than one copy of a generator. It should however be clear from the context that this is intended [13].

$$c = \sigma(g_1, g_2, \dots, g_n) \quad (5.35)$$

$$c' = \sigma(g_2, g_3, g_{10}, g_{13}, g_{20}, g_{15}, g_{24}, g_{27}, g_{28}) \quad (5.36)$$

Configuration is based on the values function ρ which defines the pair of bond values which can be related. For example expressions 5.27 or the table of values in 5.5. It shows all two generators that can bond making up a configuration consisting of two bonds locally regular for any couple of bonds $(i, j) - (i', j')$ we have 5.3 is set to be locally regular.

For a configuration to be regular in addition to local regularity it needs to be globally regular. For this the *connection type* is used. Connection type can be linear for *linear* chain graphs or *tree* for tree shaped graphs. This represents the last piece to also define *regularity*. A configuration is defined to be globally regular if $\sigma \in \Sigma$; where Σ represents the physical arrangement of generators which in the case of a modelling language is linear. A configuration is called regular if it is both locally and globally regular therefore for a configuration space $C(R)$ where $R = \langle G, S, \rho, \Sigma \rangle$ is referred to as regularity; where S represents *similarity* group and G represents the *generator space*.

Comparing pattern theory to Chamsky's formal grammar, generators of pattern theory are the rules of transformation. They are the formal grammar. Transfor-

mations allowed by the rules are constrained by the consistency placed with bonds [101]. Generators are grammatical rules whereas the bond-values are subsets of the terminals and non-terminals.

5.4.1 Probabilistic Regularity

The concept of configuration is built on combinatory idea where generators bond to each other based on the evaluated bond relation ρ on the product of $B \times B$. A bond between two generators can be either TRUE or FALSE with the binary function ρ . There is a possibility to extend this to some continuum valued function called acceptor function that takes non-negative real numbers. This approach may also find application in configurations representing the Plutonium (Pu) and Highly Enriched Uranium (HEU) weapons acquisition path. This can be in particular interesting to the evaluation of the path combining the nuclear indicators associated to different nuclear activities in order to parameterize the configuration discovering acquisition paths which are more probable than others. This means characterizing a bond not only as a fit of material going in and out of the generator but rather create configurations where some bonds are stronger than others based on the available indicators collected through inspection or open source. This formalism can be used to apply algorithms to further refine and identify most plausible acquisition path.

The powerful concept behind this theory and its application is to build probabilistic structures on top of the algebraic one of $C(R)$. In other words there is a possibility of having a relaxed regularity where the binary function is extended to some continuum valued function *acceptor* denoted with A . If G is a finite set and σ is a fixed as defined in [102] associating probabilities to a configuration c would be expressed as shown in 5.37.

$$p(c) = \frac{1}{Z} \prod_{\langle k, k' \rangle} A[\beta_j(g_i), \beta_{j'}(g_{i'})] \prod_i Q(g_i) \quad (5.37)$$

$$\sum_c p(c) = 1 \quad (5.38)$$

Where Z is the constant that normalizes the probabilities so that the sum of all probabilities is equal to 1 as shown with expression 5.38 defined in [102]. Q represents a non-negative weight function with the role of making probabilities not only depend upon the couplings $\beta - \beta'$ but also the generators themselves. Furthermore $\langle k, k' \rangle$ is short for $k = (i, j)$ and $k' = (i', j')$.

5.4.2 Self-assembling Configurations

Further to the codification of the NFCM models where PT can be used as an intermediate language for transformation or analysis of inspection process structures, it can also be considered a construction formalism. An example would be to introduce in addition to the 31 identified generators described in the previous section two more generators namely g_{Pu} and g_{HEU} . These two generators represent the actual acquisition of the Pu or HEU. Such generators in a process model would be equivalent to the End event. These generators are also defined with properties consisting of a structure characterized by bonds to other generators (nuclear activities) that can generate weapons grade material in its final stage. By introducing these two generators in a generator space of a state, based on the binary function or Acceptor function (as suggested above) the acquisition path can be reversly build from simple structures into complex structures or configurations representing potential acquisition paths. This may seem of no great benefit dealing with a small state or even a more complex state on its own however may serve as a formalizm to discover new paths on a global scale between any two or more states. Basic building blocks or generators representing nuclear activities formalize structures modelled by nuclear experts regardless of the notation of the modelling language used.

Acquisition path configurations represent information structures that need to be stored and retrieved. This introduces the need to find storage mechanisms for configurations created which can then be queried to answer expert questions. Sim-

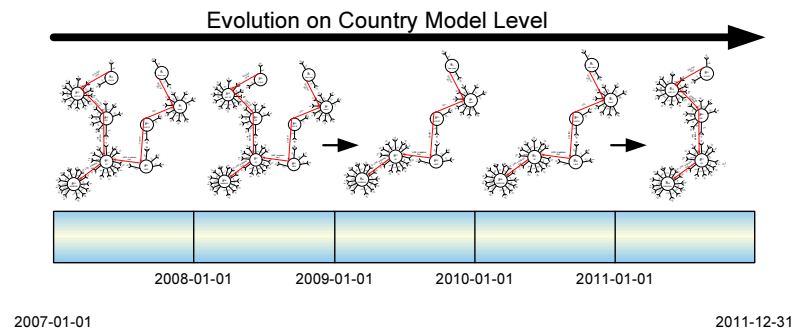


Figure 5.19. Example application as a result of PT formalism. NFCM Model-level evolution can be analysed over a timeline for a country or group of countries. Process structures can be seen as configurations representing NFCM models created by experts which are comparable to other models.

ilar to the archetypes introduced with the electronic health records configuration can represent information structures that can be queried with a predefined query language similar to SQL.

Evaluation of the Approach

This chapter presents the evaluation of the suggested approach in modelling complex inspection processes. Conceptually the approach consists of two modelling languages. First, the modelling language at the visual/concrete level that is user friendly and used by domain experts and second a modelling language at an abstract level that can be mathematically formalized. The complementary nature of these languages is discussed in the next sections of the chapter. Use cases of modelling extended with the pattern theory formalism are considered to evaluate the unique use of the approach to analyse models and create process models that are knowledge based. Other possible formalisms are also discussed.

6.1 Application of Pattern Theory in Designing Complex Processes

It is safe to say that any business entity today operates in a reality that is complex and challenging. Understanding the environment and factors that can make or break a business requires capturing realistic knowledge, which must be translated to business operations performed on daily basis. Generally speaking modelling is known to be an effective way of representing reality. Specifically, process modelling for any entity is a continuous task, which enhances the ability to adjust to a context that is dynamic in midst of regulatory and technological changes. Recognizing such changes and transferring this knowledge to process models still remains a challenge.

In the absence of historical data, provision of modelling tools and methods can help minimize the gap between business goals and processes that eventually lead to their achievement.

In contrast to the private sector where the ultimate objective is profit, the challenge of understanding the reality in the domain of nuclear verification is likewise great. In order to design inspection processes, safeguards analysts need to understand the nuclear activities in a state and interpret these according to IAEA's verification obligations. This requires that domain knowledge is used to create inspection processes. In the past decades the nuclear verification was primarily based on criteria related to nuclear material accountancy. The state declares the activities and nuclear material they have to which the inspectorate responds with inspection processes that are based on the goals of timeliness (time required to acquire a weapons) and quantity (amount necessary to build a weapon). The new safeguards, which is much more information driven requires dynamic, and knowledge based inspection process models incorporating both quantitative and qualitative findings. Here we create a model-based approach to facilitate understanding of patterns related to nuclear activities in a country and applying this knowledge for designing inspection processes that are agile. Specifically the approach here suggests the use of domain specific models such as the nuclear fuel cycle model in order to benefit at the business (inspection) process design level.

Understanding domain specific models created to describe nuclear activities in a country is a pre-requisite to the subsequent step of designing inspection processes. Such an approach can be applied to any other type of inspection processes that is considered knowledge intensive and complex. In the context of nuclear inspections two *use cases* will be evaluated, *Process Analysis* and *Process Configuration* discussed below.

6.1.1 Process Analysis

This use case covers the requirement of using nuclear process models for understanding the objectives of the verification regime in a country. These objectives are subsequently used for designing processes that fulfil them. In order to model inspection processes or in cases where they exist improve them we start by analysing

the domain specific nuclear fuel cycle model. These models are created by safeguards analysts to both document and synthesize understanding of the processes in a country. This is a requirement for planning verification activities. Pattern theory as a graphical and mathematical formalism is used to represent process structures as patterns. Specifically of interest are patterns that show potential weapons acquisition paths. In the terminology of PT these patterns are considered regular configurations in the domain of interest. Moreover regular configurations combine generators into structures according to the rules that can be deterministic or random. Configurations represent the unobservable image, which is formal enough to be processed whereas the observable image (i.e. model) is domain expert friendly. In this context let us define some simplified query scenarios that will support decision making for modelling inspection activities:

Query Scenario 1: *Find all potential acquisition paths for country X.* Based on the rules of local regularity between generators that represent nuclear activities (modelling elements) this query can be answered. Graphical formalism to represent a generator for the pre-conversion activity is shown in Figure 6.1. Structure of this generator defines the possible connections or bonds to other activities. The top panel of Figure 6.1 shows the truth table constraining all possible connections between generators g_1 (pre-conversion) and g_7 (Enrichment through EMIS). This particular generator has in-arity of 2 and out-arity of 8. Rules of regularity represented through the generator structure were based on nuclear material that is generated as a result of one activity and required as an input to another. In the example above UCl_4 (Uranium Tetrachloride) which is generated during pre-conversion is an input to enrichment activity using EMIS (Electromagnetic Isotope Separation). Another material that can be used as input is UF_6 (Uranium Hexafluoride) however it is less desirable. Stronger bonds between generators can be also formalized in pattern theory by relaxing regularity described in the next query scenario.

By starting with two constant generators (g_{Pu}) (g_{HEU}) representing the events of actually acquiring Pu or HEU necessary for a weapon, a path can be built in a reverse order as per activities modelled by the domain expert. Depending on elements shown on the model the query result can be 1 or n potential acquisition paths. High level steps of the mechanism to answer such a query are as follows:

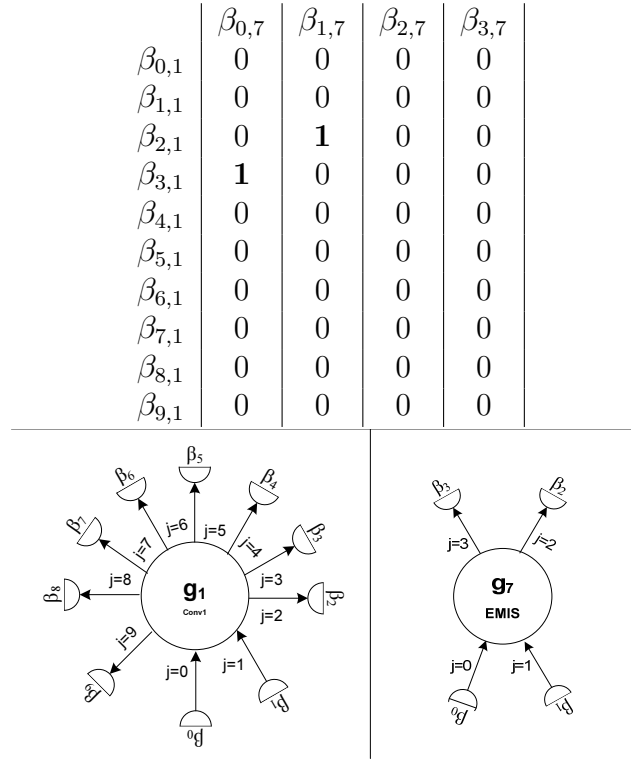


Figure 6.1. Truth table defining local regularity between generator g_1 (pre-conversion) and generator g_7 (EMIS enrichment). On the bottom panel the corresponding structure of the generators representing the activities are shown.

Step 1 - Identify all elements in a model representing nuclear activities

Step 2 - Map elements found in Step 1 to generators ($g_1, g_2, g_3 \dots$)

Step 3 - Identify all generators that have a bond to the generators g_{Pu} and g_{HEU} .

Step 4 - For each generator identified in step 3 find bonds to all other generators. Iterate until no new bonds are discovered.

The query may return no results should there be no nuclear activities modelled that are in the final stage of the acquisition path. Also to limit the number of potential paths the user can choose to restrict the query such as Find all potential Pu acquisition paths for country X. The position taken is that it is of no relevance if the modelled nuclear activities are declared (regularly done by each country)

or undeclared activities - suspected by the expert to be present in a country (e.g. through open source, satellite imagery etc.). They represent understanding of analysts as a result of synthesise performed using inspection data and open-source information. Modelling environment and notation of the language is user friendly and familiar to experts in order to facilitate the transfer of knowledge useful for us. Moreover, the patterns represented with configurations of generators are not visible to the modellers and are machine interpretable.

Query Scenario 2: *Find the most plausible (probable) acquisition path for country X.* As discussed previously in addition to the formalization with the use of metamodels an additional level of formalism can be achieved with the Object Constrained Language (OCL). However, such an approach requires us to step away from the graphical representation that is more in line with model based approach and comprehensive in the case of pattern theory. With generators and their bonds we can formalize not only data structures but also rules that allow generators to be combined into more complex structures. Generators seem to be also a good formalism for transformation to object-oriented data structures. Each element is described by a generator and subsequently each generator in a configuration represents an instance of the generator class whereas the behaviour of the object (methods) would be defined by the generator bonds.

What is exceptional about pattern theory, which can help us answer the above question, is that the binary relation between generators and therefore the corresponding modelled activities can be relaxed. Based on the binary function Rho the stringent condition can be relaxed to probability measures. The binary function that accepts only true or false values can be extended to a continuum valued function *Acceptor* $A()$. Probabilities can be associated to configurations by a structured formula shown in expression 5.37. $P(c)$ describes the joint probability distribution. This way the we can ask what the conditional distribution of a random subConfiguration $c = (g_1 - \text{Conv1}, g_7 - \text{EMIS})$ is given the remainder configuration.

In order to answer the question/query as in the previous example there has to be also a mechanism to answer questions placed against the model. The two high level steps would be:

Step 1 - get results from *Query 1*

Step 2 - input vectors and attaches weight to define probabilities based on the findings of inspectors.

Pattern Theory formalization can be used for the application of Bayesian Inference. Given the activities the network can be used to determine the probability of the presence of a weapons acquisition path. A good example would be using the so called indicators as classified by the IAEA and assigned states Strong (S), Medium (M) and Weak (W). These variables can be assigned to activities modelled and assessment of an acquisition path would be in terms of the probability distribution over the event of acquiring Pu or HEU. Ability to apply complex algorithms is large with pattern theory such that questions can be more specific Find an acquisition path for Pu in Country X given indicators a, b and c.

In order that the results of these questions are used for designing inspection processes there has to be a framework by which results can be incorporated in the design of quality inspection processes.

The new information driven safeguards is expected to be objective driven rather than criteria driven. What this means is that objectives which are learnt from the domain specific models have to be used to match processes that will help meet these objectives. The *integrated Safeguards Modelling Method (iSMM)* does not envisage any automated creation of objectives using the inspection objectives model. The results of the analysis performed on the Nuclear Fuel Cycle Model are used to support the decision of safeguards analysts in designing inspection processes. Objectives identified and modelled using the Inspection Objectives Model are annotated to inspection processes and tasks that will help create the link between the two layers. To achieve this the thesis proposes the Value-Focused Thinking as a framework that will guide breaking down higher level objectives to more detailed and technical objectives in order to create a link to the processes and tasks that fulfil these. Such a approach does not only guide the design of inspection processes but also offers means of introducing metrics for measuring how well objectives are met.

6.1.2 Process Configuration

Formalization of process models with Pattern Theory is not limited to nuclear processes can also be applied to any other type of process models. A brief example is shown in Open Models Feasibility Study. In the case of the iSMM the language for modelling business processes is conveniently named inspection process modelling language (IPM). The constructs and the metamodels of the two are the same. Small differences exist on the notation and attributes of the modelling elements.

Each of the modelling elements in IPM can be likewise formalized by creating generators mapping to each modelling element. For example elements such as Activity, Parallelity, Merge will be represented by generators g_1 , g_2 and g_3 . As it was in the case of using patterns for analysing models, inspection processes models can be formalized as configurations combining bindable generators into process structures. The interesting aspect about defining the generators and their structure through bonds here is that the same rules of regularity could apply to any business/inspection process model regardless of the notation used (EPC, BPMN etc.). They would be generic in the domain of interest with bond structures that define binary relations between the generator such as g_0 (Start), g_1 (Activity), g_2 (Parallelity) and so forth.

Here patterns are more seen as means of validating the process models in terms of their structure and composition and should provide guidance for modelling. Abstract processes named "inspection pathways" map out the sequence, timing and expected outcomes in terms of safeguards objectives. The idea is to standardize inspection processes that are cost-effective. Based on the example of so called clinical pathways which describe the treatment for a patient, inspection pathways are instruments that describe the common way of dealing with known problems in the domain of verification. The structure of a pathway that is rich with heuristics and procedural knowledge can be used as templates to create process model instances which can then be specifically adjusted to the situation at hand. They represent formalized structures of higher order that facilitate faster modelling but also improve the quality of created models. It has to be said that with generic formalization of the elements used in modelling inspection/business processes semantics cannot be ignored (i.e. names of the activities). There will be an apparent semantic loss should modelled elements and their combination simply be mapped

to generators represented as configurations. An example configuration consisting of generators Start, Activity 1, Activity 2, Activity 3, End would require that a generator is used more than once and that identifying marks of the elements (e.g. name) is preserved. Pattern Theory has also a provision that the same generator can appear more than once in a configuration. To keep them separate identifying marks as parts of attributes are used. The result is a formalization which defines the relationship rules between any two elements in the model. Moreover, it represents pathways as regular configuration structures that are modelling language independent and mathematically formalized for the application of complex algorithms.

Query Scenario 1: *Find all inspection pathways that lead to objective Y.* Any such query would require that the model is explicitly associated to a objective Y. Or at least elements in the model are. By formalizing the process models called pathways with PT it is the configuration which is associated to an objective. This allows for a result to the query that covers all models that have the same process structure as the configuration c. In a way we prefer to know about the process structure rather than the details of the model.

Query Scenario 2: *Find differences between inspection Pathway R and Model Instance Z.* The objective of such a query is to find out all the changes that need to be applied to model instances based on any regulatory or technological change which is reflected in the inspection pathways. New pathway configuration is compared to the configuration of model instances to identify difference in the structure that are helpful for identifying any shortcomings.

6.2 Pattern Theory and Other Formalizms

There are various formalization approaches that could be also used to achieve the any of the evaluated use cases. Their application depends on the problem at hand. Pattern theory contains graphical formalism similar to using graphs with the important distinction that generators compared to nodes representing elements of a model would be typed (Activity, Parallelity, etc.) and can carry other attributes that can add semantics to the formal representation. Using graph theory in this context can be said is semantically inferior to pattern theory. A property of a

generator is its structure admitting for the definition of so-called bonds, which define connections to and from a generator. In a model a generators can be a primitive that represents a pixel of the modelled elements (image) or conceptually the element itself. In our case generators represent modelling elements which in the example chosen are the activities that can lead to the acquisition of a weapons grade nuclear material.

Pattern theory as introduced originally had a purpose of identifying patterns rather than what is commonly known as pattern recognition. Taking this as a starting position it is important to note that in the context of representing models created by domain experts this formalism serves the transformation of models into patterns that can be analysed by various algorithms and mechanisms. Formalized in a precise language that will allow us to transform user-friendly models to mathematically concise elements. As cautiously noted by Grenander in [102] Einstein was thinking more about physics when he claimed that the most remarkable thing about the universe is that it can be understood. However, languages are a biological product. What he refers to is natural languages so this observation can only be partially applied to modelling languages shown here. In our case models represent subjective understanding that we take for granted and try to offer means to mathematically formalize the same. This requires that languages used by the modeller are expressive enough in addition to us being able to codify them into analysable patterns.

6.2.1 Formal Grammars and Graphs

Formal grammars attempt similarly to understand language structures in a logical way in terms of primitives (i.e. word classes). Rules are used to describe how to form strings according to the language syntax. More precisely production rules are applied to generate strings that are recognized by the language. Moreover context-free grammars use precise mechanisms to describe the methods by which phrases are built from smaller block structure of sentences. When dealing with models that are created using predefined modelling languages we try to do more of the same in order that our models are understandable according to the defined syntax. Since the overall approach of the study is to use models or diagrammatic means

for representation, a good example of a formalism is graph grammars. It extends the theory of formal languages in order to deal with the structures more general than strings such as graphs. By describing structures in a simplified way nodes in a graph correspond to substructures whereas the edges show the relationship between them. Grammars are the operations on the graph. In Bardohl [70] graph grammar formalism is used to represent visual languages. Abstract syntax is used to describe the concrete syntax of the visual modelling elements. On one hand graphs are used to show the structure of the visual sentences. On the other hand grammars are the operations on them. These operations represent graph transformations. The so-called pattern graph on the *L* (*left*) and the replacement graph on the *R* (*right*) of the rule are used to formalize the transformation. Figure 6.2 shows a simplified representation of modelling elements post-conversion and EMIS in the NFCM model using a logical structure graph as proposed in [70].

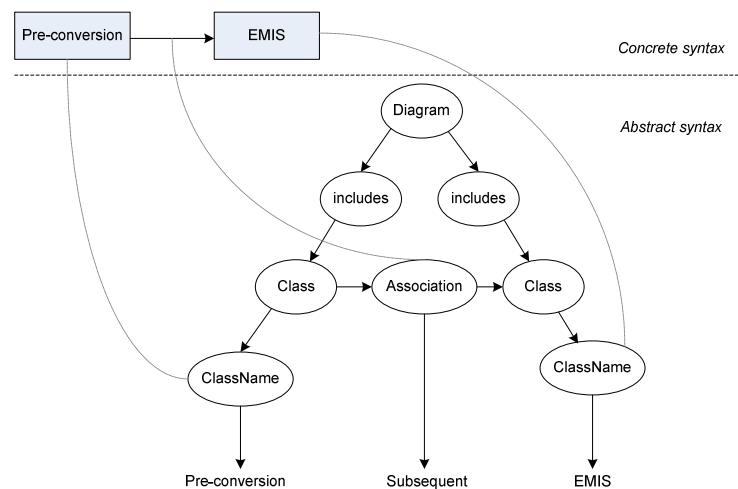


Figure 6.2. Logical structure graph representing the visual elements pre-conversion and EMIS.

Figure 6.2 shows an attributed graph where nodes represent the two elements of the modelling language namely the pre-conversion activity and EMIS for enrichment of the material generated by the previous activity. The relationship is also shown as a node representing the association of these two elements. This representation shows the structure and the building blocks however it is short

of operations that need to yet be defined. This representation in comparison to pattern theory is shown in the next Figure 6.3 where the same two elements are formalized with generators of the theory. The two modelling elements each map to a generator. Their properties are the bonds that represent a structure set describing the possible connections between these generators. The figure shows how the two generator bonds are closed to represent the regular connection constrained through the binary function or the less stringent *Acceptor()* function.

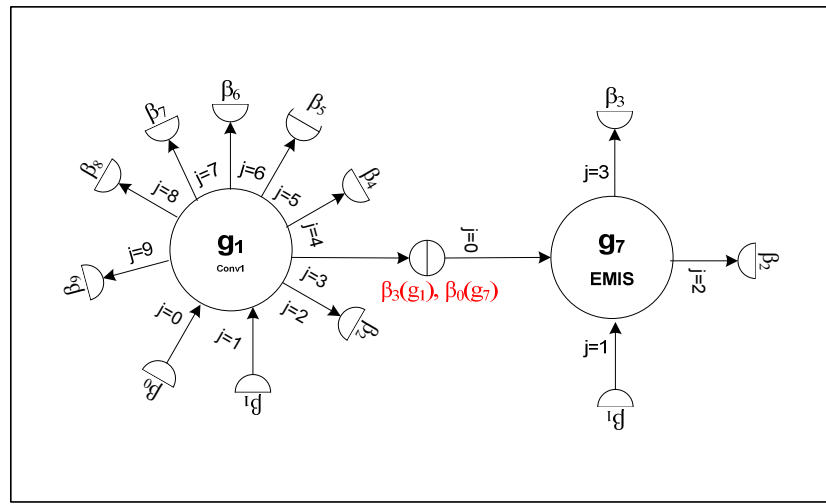


Figure 6.3. Pattern Theory formalism representing the bond between the pre-conversion and EMIS generator.

As it can be observed generators of the pattern theory are also nodes of the graph however they also contain a structure as a property. In other words the generators are the grammars. They represent grammars placed on a graph. In this way we can represent the logical sentence structure but also can formalize all possible connections to neighbouring generators. This formalism is not apparent with graph grammar where rules or operations would have to be explicitly represented in a non- graphical way to support the graph. Furthermore, another important property of a generator is that it can carry attributes. This being very useful for typing generators according to the visual elements to which they map to. It can be said that PT graphical formalism allows for easy transformation of concrete syntax to abstract due to the visual similarity of the modelling elements and the generators. Graphs offer also a level of visualization however are short of

the connection rules obvious in the case of generators and their bonds.

6.2.2 Petri Nets as a Representative Formalization Language

Petri net is another abstract formal model that can be used to represent visual languages. Some research was performed in this area where Petri nets are linked to graph grammars to formalize animations of the visual modelling environment. The use of grammars as an intermediary formalism to represent visual elements speaks that nets may not be best at representing visual models [108].

A Petri net graph contains two nodes, *places* and *transitions*. Arcs connect nodes. If the arc is directed from a place to a transition it is considered input. It is treated as an output if the arc is directed from a transition to a place. There can only be a connection between a place and a transition never from a place to a place or transition to a transition. Places and transitions can be thought of as conditions and events in the respective order.

In addition to this static representation of Petri nets, behaviour can be modelled with so called tokens that places. They fire transitions, namely trigger events. Only when all places have a token the linked transition can be fired moving the tokens to the end of the output arc. This serves a useful representation of the behaviour of a system dealing with issues such as concurrency. But is not limited to computer systems and has found application in many fields such as molecular biology etc.

Let us briefly look at an example of a simplified Petri net representing two activities of the nuclear fuel cycle as shown before with the use of graph grammar and pattern theory. Figure 6.4 shows a Petri net of the modelling elements pre-conversion and EMIS. Here we see that modelling elements representing the activities are mapped to a transition node where as the subsequent relation which is based on the nuclear material is represented by places. Nuclear material used by the activity is represented as a condition to the event of pre-conversion or enrichment with EMIS.

The static representation of the net in Figure 6.4 shows how UOC (Uranium concentrate) or ThConc (Thorium concentrate) as a result of mining activity can be used as an input to pre-conversion. The UF_6 or UCl_4 that is an output of

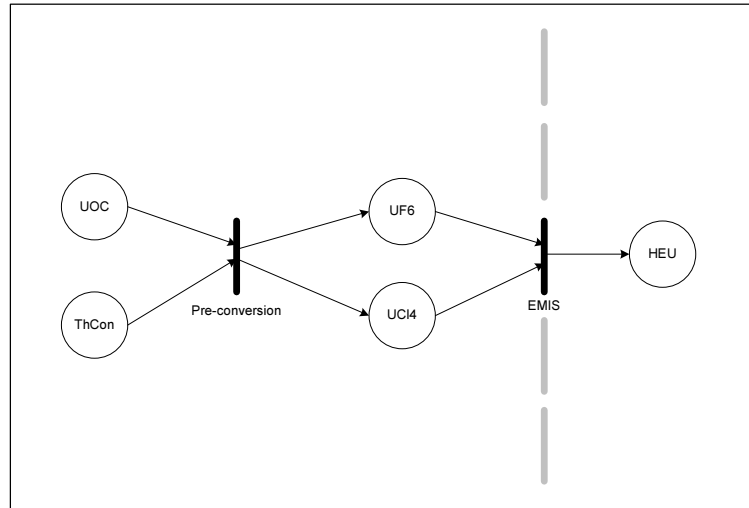


Figure 6.4. Petri net representation of the pre-conversion and EMIS. Modelling elements were mapped to transition nodes whereas the relations were represented as places. The grayed out transitions represent the missing events not obvious with this formalism.

the transition node pre-conversion is then used as an input to the transition node EMIS. Possible enrichment activities are numerous therefore there would have to be a transition node for each which would make the net less comprehensive something that can be better represented with pattern theory generators and their bonds. The structure representation with the net adds little information to a graph representation of the acquisition path activities shown before. Moreover, it can be said that in the case of pattern theory there is a convenient one- to-one mapping of the visual modelling elements to generators, which is less so in the case of a Petri net where the visual model is transformed to two types of nodes.

Petri nets have also behavioural properties, which can be used to simulate models of the system under study. This was briefly explained in the introduction where the tokens are used to represent states and transitions to new states. Taking the models created with the NFCM to represent acquisition paths, Petri nets can be used to also represent an acquisition path by triggering possible events in the net to reach the weapons grade materials Pu and HEU. The so-called reachability property can help answer questions such as what markings are reachable in the Petri net or what sequence of transition firings are possible [109]. Therefore, these properties of the net can help us also answer questions such that we identify the

alternative paths of reaching weapons grade material. Despite this characteristic of a petri net that is applicable it can be said that simulation of the kind is important when dealing with automata in representing

Although main use of Petri nets is deterministic literature shows also extensions to the net to deal with non-deterministic measures. Timed and Stochastic Petri nets can be used to also to add nondeterministic time through randomness of the transition. Random probability distribution is used to time nets and the graph can be used as a Markov chain. Such techniques applied on the net can help us answers some of the questions which were answered by pattern theory. For example the question related to the most probable path of acquisition of HEU and Pu in a country. Very much like the suggested approach with Pattern Theory.

6.3 Conclusion

As mentioned at the beginning of this section Pattern Theory is more about identifying patterns or generating patterns that represent realistic structures. These in our case are constrained by the modelling language. What is unique about the formalized acquisition paths is that the generated patterns resemble also the visual model created by a domain expert. They represent signatures that are regular and can be treated also for variability. Configurations represent also probabilistic structures, which allow for expressing variation. Similarly stochastic Petri nets are also able to achieve the same however it is not envisaged in the originally introduced formalism by Petri and therefore any such extension makes it more complex in contrast to pattern theory. Moreover, the "*connectionism*" apparent in pattern theory emphasizes the combinatory nature of pattern theory where primitive elements are assembled into configurations. Petri net both as a model or a representation of a model has to be complete in order for us to be able to formalize it. This is not necessarily so with PT. The "*constructionism*" of the theory as described in the open models feasibility study lets us create relations also between independent generators characterized with bonds. To illustrate this one can imagine that two modelling elements that are displayed on a diagram without any connection between them would still be interpretable by pattern theory. From the structure of the generators we know if the two elements can bond. Moreover each generator is

has its own identity. This is not the case with Petri nets where two independent petri nets would have to be created. The relation between any two elements would have to be explicitly defined. In the case of PT where visual elements map to generators we also know the rules / grammar of their bonding represented on the generator. The ability to generate patterns is one of the principles on which the theory was built. Figure 6.5 shows a generator as a building block envisaged in the theory and what the equivalent of it would be in a Petri net (an excerpt of the net).

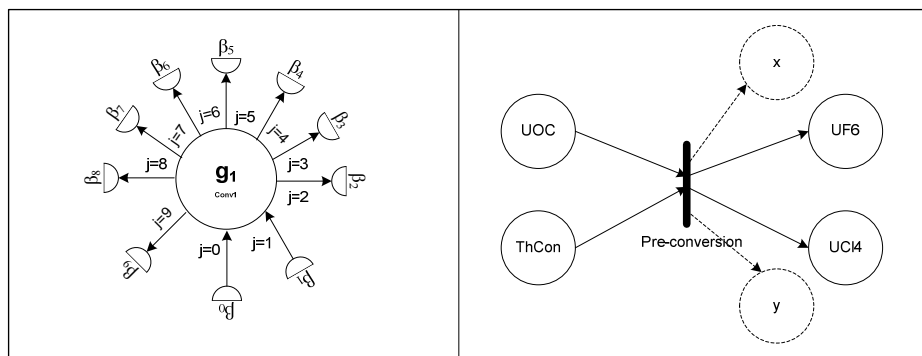


Figure 6.5. On the left panel the typical generator formalism for a nuclear activity mapped to the corresponding modelling elements is shown. The β values correspond to the input nuclear material. On the right panel the equivalent of a elementary block (generator) is illustrated to demonstrate the missing definition with the Petri net formalism.

Furthermore, Pattern Theory allows probability distributions to also allow for variability of the represented structures. As exemplified before probability distributions can be used to characterize the local bindings between generators as being more probable than other possible bindings. On larger scale configurations can be seen as regular structures that are also measured in terms of their probability in comparison to similar configurations. Such a notion in Petri nets would translate to bindings between transitions and events where the relation between them is dependant on places. It is worth mentioning here also the regularity principle present in pattern theory. A regular configuration warrants a valid structure that can be analysed since we know that all the connections followed local regularity. In the

presence of configurations the formalism also allows for the Q non-negative weight function defined on the graph that makes probabilities not only depend only on the couplings β - β' but also generators themselves.

Pattern theory represents a formalism that is graphically very descriptive for representing process structures while allowing for definition of regularity in addition to variability. Between purely graph representations and graph grammars which are rule intensive and formalisms such as Petri nets that are unique in studying behavioural properties, pattern theory finds its place as a mixture that strikes the optimal balance of both properties. It serves as an intermediary language between domain specific languages and formal languages.

Modelling Environment and Example Case

This chapter discusses the implementation environment of the iSMM. It also presents some application scenarios based on the suggested approach presented in the previous chapters. Modelling languages of which the framework consists are conceptually independent of the platform and technology however the work done here is based on the BPMS paradigm and the meta-model ADONIS primarily used for business process engineering. ADONIS represents a tool for holistic Business Process Management by helping streamline business processes, organizational restructuring aiming effort and cost reduction [76]. For the implementation of the inspection modelling method ADOxx which represents an evolution of the ADONIS was used. The next section presents ADOxx platform and gives implementation details.

7.1 ADOxx platform

”ADOxx platform is a metamodeling-based development configuration environment to create domain-specific modelling tools” [110]. This platform is considered to be scalable, adaptable supporting multi user support. It represents a web-enabled environment offering a holistic approach for capturing conceptual elements into methods that are machine processable.

Figure 7.1 shows the envisaged architectural context. Conceptual architecture

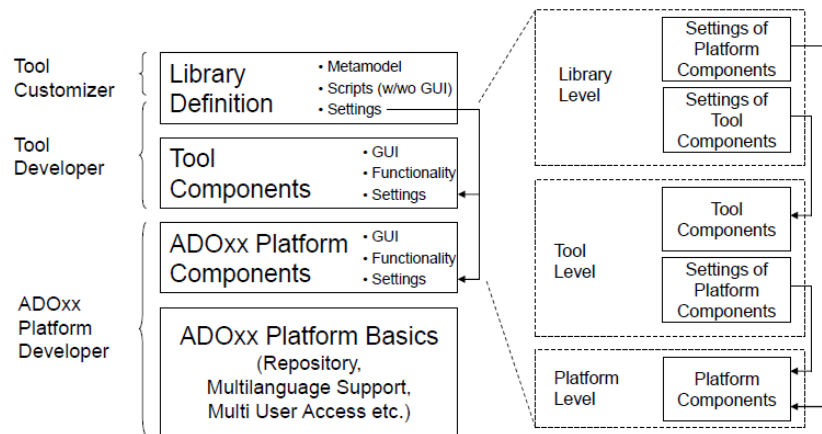


Figure 7.1. ADOxx Architectural Levels and Responsibilities ©BOC Group

is divided into a library level, tool level and platform level. Tool customizers, developers and the actual platform developers are shown as the responsibilities necessary for implementation on this platform.

The new platform allows for advanced customization of the tool with an open architecture enabling end to end of modelling methods that offer functionality. By creating formal languages not only real world structures are represented but also processed [110].

For the inspection modelling framework an new application library was created in the platform consisting of modelling languages that formalise the inspection concepts. Traditionally in the ADONIS environment based on the BPMS paradigm libraries consist of two components, the BP (Business Process) and WE (Working Environment). One was meant to deal with process models and cover all the elements of the dynamic models whereas more static models were created in the WE library (e.g. models representing organizational structures). This separation of the two represents no technical limitations in integrating models from each within the library or other libraries. As shown in figure 7.2 libraries BP and WE library consist of classes contained in a model types. Instance of a model type is a model. At each layer shown there are attributes (i.e. library, class, model or

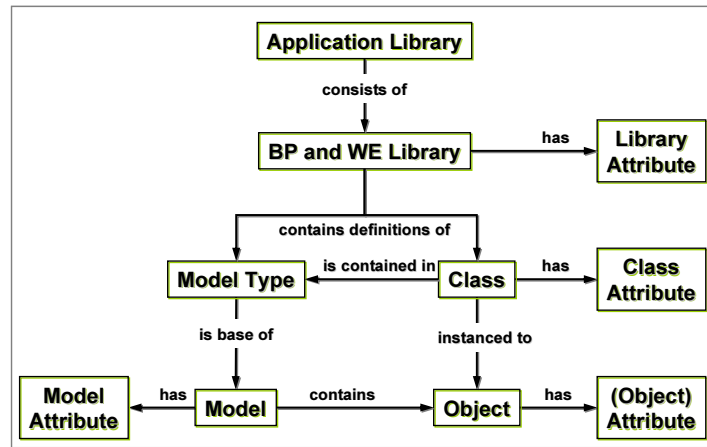


Figure 7.2. Application Library in ADOxx ©BOC Group

object).

The inspection modelling framework based on the concepts introduced earlier is represented with a great number of models. For the inspection modelling method a dedicated library was created with the languages necessary to formalise a safeguards approach. For the inspection modelling framework as a whole three libraries including the inspection method are necessary. PROMOTE library that contains all modelling languages of the approach and a library which represents the technical layer with languages such as UML, BPEL etc. At present there seems to be a limitation in integrating application libraries in ADOxx however models can be easily moved from one library to another. For sake of simplicity the approach here was to limit the implementation by integrating two libraries namely the inspection modelling method and PROMOTE which is extended for other model types such as OWL, UML etc.

ADONIS meta-model was extended also for models represents inspection views. The (BP and WE discussed above) have been used as the super classes under which all elements of the inspection modelling method are created. In the case of Inspection Process Model based on the Business Process Model elements of the class hierarchy are duplicated with slight notational changes in addition to new attributes.

The ADOxx meta class container provides attributes which are inherited by all

subclasses important to the visual representation of the modelling elements in the modelling language. Inspection models were combined with the business process modelling language based on the notation of BPMN and ADONIS. These processes are named inspection processes and reference other inspection specific models such as inspection objectives, nuclear fuel cycle model, the organizational model and the nuclear facility model. Each of the modelling elements represent an implementation class under the ADOxx. They are characterized with attributes which can accept accept values defining the semantics of each modelling element [110]. Figure 7.4 shows an extract of the classes of the inspection modelling method at the implementation level. Each of the classes inherits the attributes such as GraphRep and AnimRep which can be used to define the notation and animation properties of the modelling element using the ADONIS scripting language. Graphical representation in the ADONIS script is provided under Appendix A. The figure shows

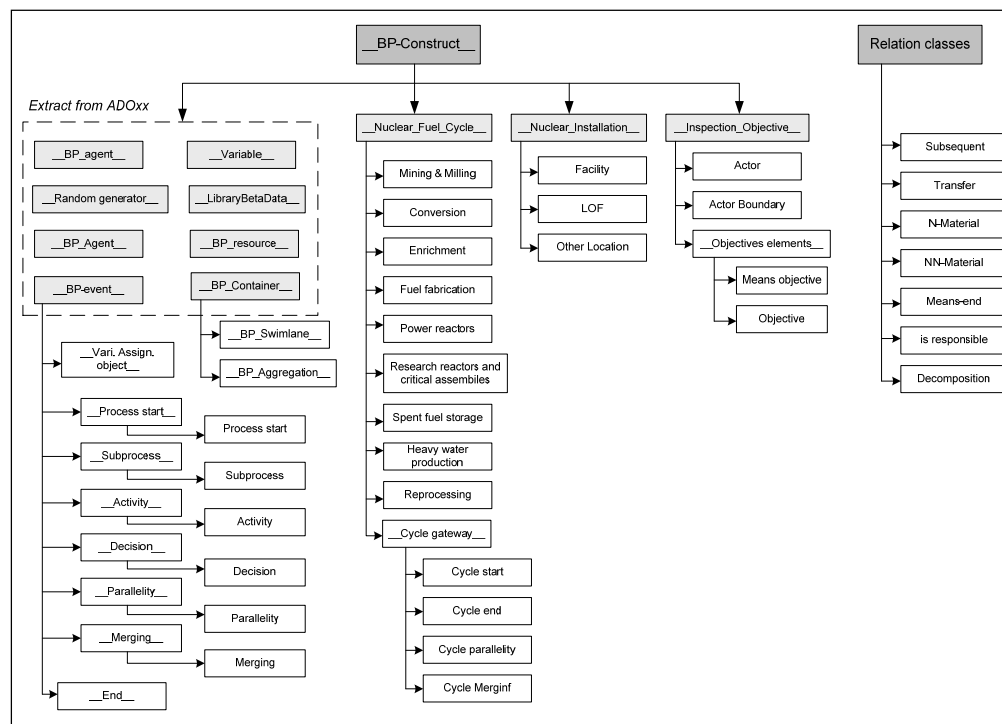


Figure 7.3. Extract of the Inspection Modelling Meta Model as an extension of the ADOxx ©BOC Group

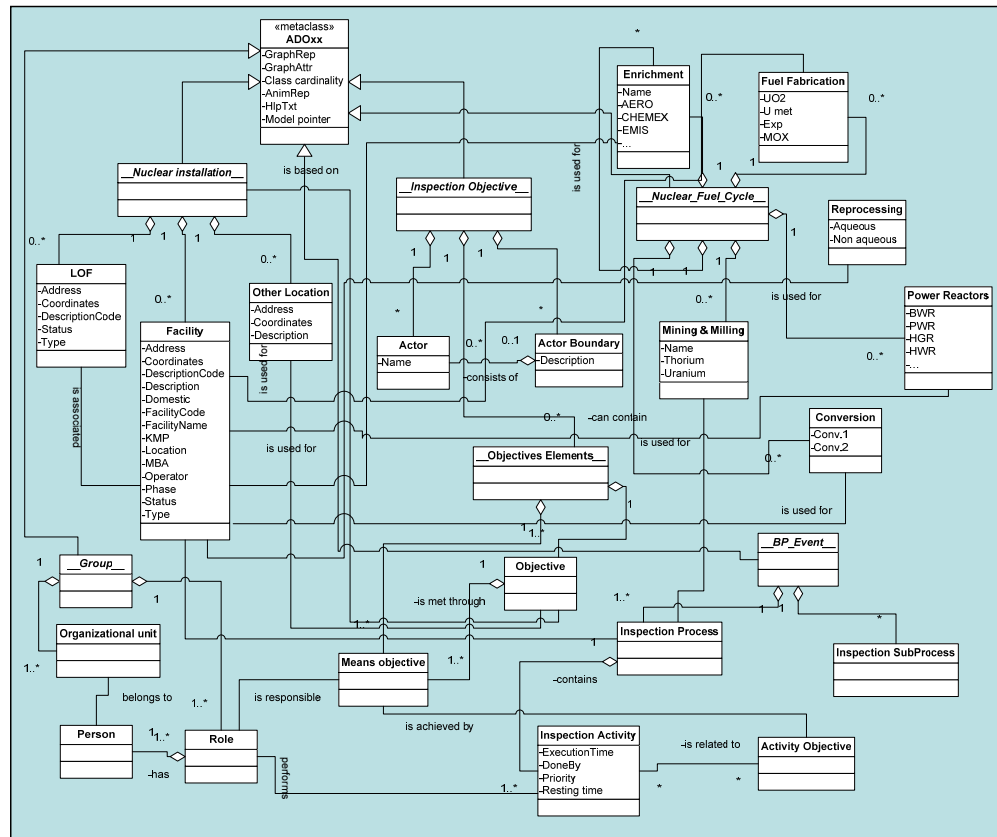


Figure 7.4. Extract of class diagram for inspection modelling method. It shows an extract of the classes newly created in ADOxx and their attributes. Some of the classes and attributes were excluded from the diagram.

Once the classes are defined the next step is to define their cardinality which can be done using ADOxx script. The attribute

Model types as defined in the administrative interface of the ADONIS can be created using the interface shown in figure 7.5. As depicted depending on the selected model type (objectives and facility model in the example) models can be created with the defined notation. Relation between the modelling elements

is created using the relationships also defined in the meta model. Next figure shows a snapshot of the administrative interface that allows for the creation of the attributes in the ADONIS meta model.

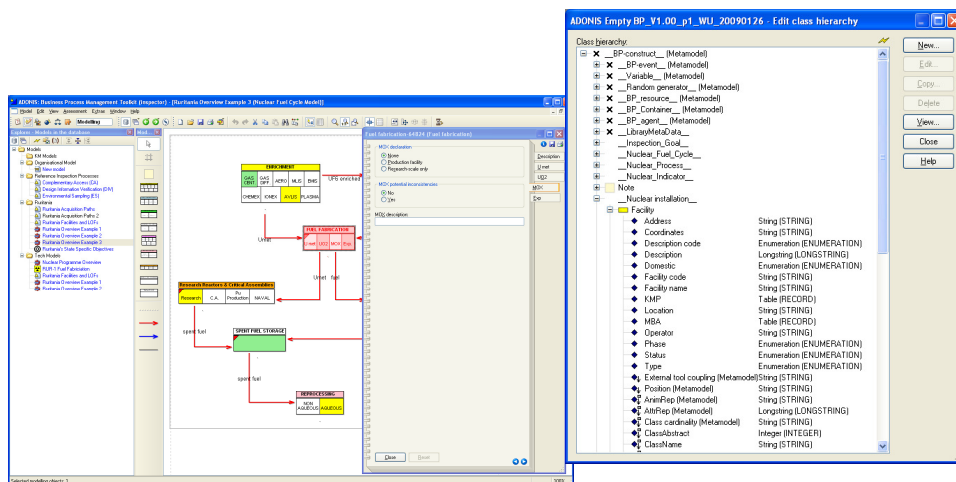


Figure 7.5. Screenshots of the ADONIS interface for creating Models and administring the modelling library.

The interface allows you for the creation of different versions and inter-referencing between models. The same models created can be easily published on the Intranet allowing inspectors to navigate through the process models and other models available.

7.3 Example Case: Ruritania

This section provides an example of the approach applied to a fictitious state called Ruritania. As described in the previous chapters there are two separate official documents named *Safeguards Approach* and *State File* that are meant to capture all state related factors, the physical model of the state and the way safeguards is implemented. Based on inspections performed and knowledge of the department about this state an approach is created that is integrated meaning it uses the optimal combination of measures that are effective and efficient in assuring the non-diversion of declared material and the absence of undeclared material and activities. For the sake of simplicity details related to the agreement with the state

[illegible]

Figure 7.6. Physical Model overview diagram and the the facility model diagram side by side. Activities of the physical model can be inter-referenced to the elements of the Facility Model.

Figure 7.6 shows on the left panel the physical model of Ruritania which is created using the modelling language NFCM. The physical model of any state is commonly represented as a static image attached to a document which can not be queried or interrogated. By using a modelling language each element of the model and the relations between the elements can be analysed and represented in a diagrammatic form using the ADONIS interface. This allows the domain experts to easily and regularly update such a models and integrate them with other models of the method.

In the example case the physical model as shown in Figure 7.6 consists of

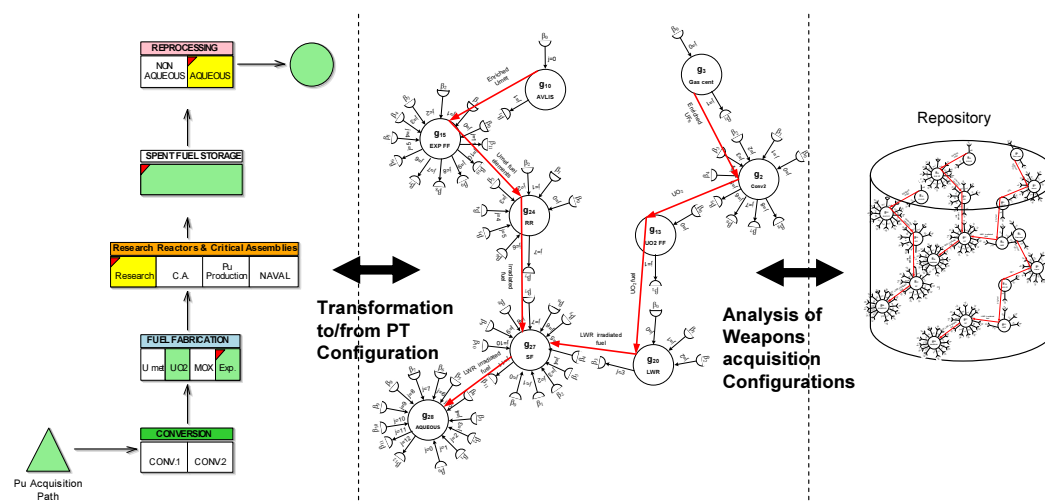


Figure 7.7. Example acquisition paths for Pu in the state of Ruritania. Mapping of the inspector created model is shown as a generator configuration which is used for analysis and stored in a repository for analysis using algorithms.

A potential acquisition path modelled is shown in Figure 7.7 where for state Ruritania the path is represented as a process model consisting of subsequent nuclear activities to reach the acquisition of Pu. Performing complex analysis of this acquisition path can be done by mapping the modelling elements to the

generators of pattern theory. Concrete modelling elements are mapped to abstract generators as shown in Chapter 5. The potential of this formalization is that it allows for further analysis not available in the modelling tool. Paths can be analyzed as generator configurations that are regular or less so. This may introduce information about the most probable paths or even paths that are most likely to be taken based on indicators discovered. To demonstrate this one acquisition path modelled is shown as a generator configuration. Such a formalism in the case of Ruritania will not only help identify whether all the paths are regular but also provide us with valuable information about possible relations with other activities in the state or outside this state. Comparison of configurations within the state or even other states can be provided in order to find any possible related activities among them.

The ability to analyse the models through the formalization explained and subsequent results lead us to the next model of iSMM which is the *Inspection Objectives Model*. This model captures the inspection objectives based on the analysis of the physical model and related models. In the safeguards approach these are usually stated in general terms. Here the model of the *objectives* that are hierarchically connected represent diagrammatically the general Safeguards objectives and lower level objectives for the state. Each of the objectives is broken down to *means objectives* necessary to achieve these higher level objectives. For example in Figure 7.8 the objectives for the state of Ruritania are shown with *ellipses* and the means to achieve these with *boxes*. In the example it can be seen that some of the objectives need to be achieved by multiple means. The means objectives are then linked to the inspection processes. Actors are shown with a *person* notation symbolizing the responsible entity for the given objectives. Actors can be roles, organizational units or systems.

In order to ensure that each objective is met, all means objectives have to link to one or more inspection processes. For instance *objective 2* is met with means objectives *CA* and *DIV*. These are both inspection processes that are detailed with the Inspection Process Model (IPM). IPM is a modelling language is similar to the business process modelling languages with an extension that provisions for the link of each process and task to the objectives.

Finally the organizational model represents the team that is necessary to per-

form any of the tasks specified under the inspection processes. Organizational model and the inspection process model represent the work plan in terms of how the Safeguards approach is implemented in Ruritania. Figure 7.9 shows the two models side by side. This gives a full overview of the operational aspects not only in terms of the tasks but also the roles in the organization that will ensure the correct implementation of each process. The process models and the organizational models are not generic reference models but represent specific activities to be performed effectively in a specific the state.

As defined in the conceptual framework this modelling method was based on there are also perspectives of KM and Technology to be represented with domain independent models. The idea is to also identify the knowledge required in performing any of the activities of thee inspection process. Moreover, modelling the technology available and required in performing any of the inspection processes in Ruritania makes explicit the relationship between inspection processes and the technology used. The modelling language chosen to represent knowledge is PRO-

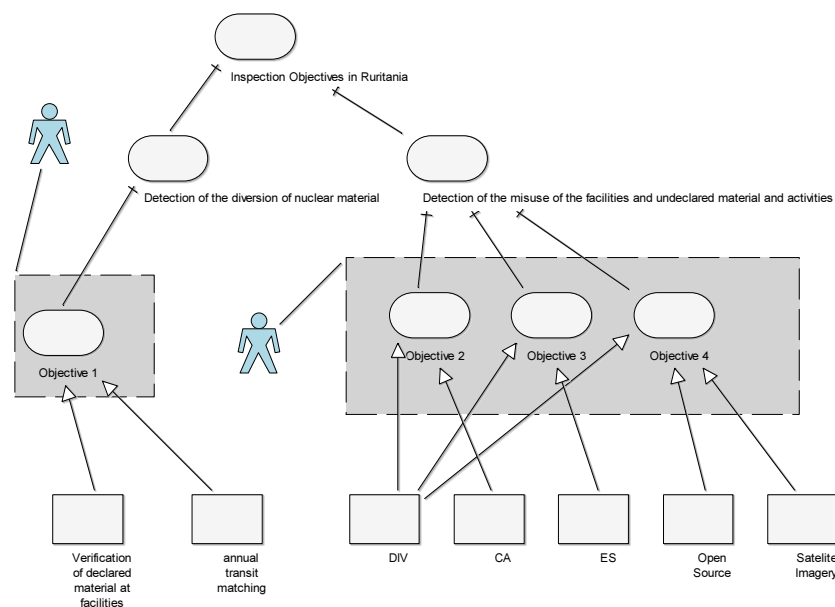


Figure 7.8. Safeguards objectives in the state of Ruritania. Inspection Objectives Model is used to represent the objectives and the means objectives based on the acquisition paths identified as well as other state related factors.

MOTE. It identifies the knowledge products necessary in performing the tasks of the inspection process. It also allows for the definition of skills of roles identified under the inspection organizational model. This is an extension to the current safeguards approach whereby knowledge requirements for implementing the safeguards approach in a state is considered an integral part. By identifying the knowledge needs and available knowledge critical to the process a *balance sheet* is created for Safeguarding the state of Ruritania.

Another domain independent modelling language is UML which is used a language to model the technology associated to the state level safeguards approach. Any technical representations of the technology applied can be represented with UML or similar modelling languages. Such details are commonly available in a form of drawings and scattered around which in this case would be readily available for use by those who implement the safeguards as well as those who provide technical services. They represent valuable information about technology and other technical services as requirements embedded in the Safeguards Approach. It can

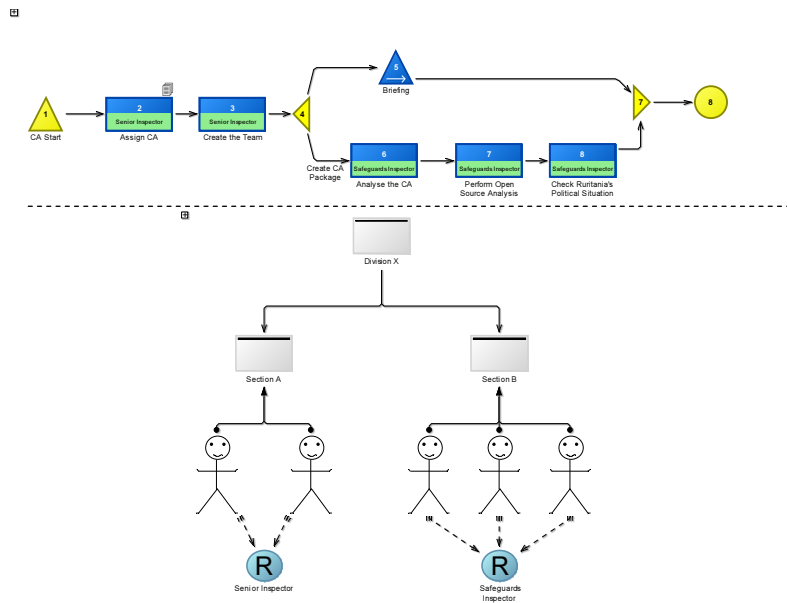


Figure 7.9. Simplified example of an inspection process that meets the objectives identified for this state. This model references the Inspection Organizational Model shown in the bottom panel. The roles and the organizational structure is modeled.

facilitate efficient use and development of new technology to accommodate changes in the approach.

7.4 Conclusion

The presented case is for a fictitious state as it is not possible to disclose realistic data about any member state of the IAEA. It however demonstrates the application of the modelling method in generating a safeguards approach for a state. It is not suggested that the IAEA currently does not have the necessary tools and means to document the strategy of implementing safeguards in a state however the example shows the advantages of the model-based method of representing verification aspects in comparison to current practices which is mainly based on formal documents and tacit knowledge.

Before	After
Text based format – approaches summarized in formal documents and procedures. Images as attachments. State related files separately stored on the LAN.	Model-based representation visualizing aspects of the approach such as objectives, the physical model, acquisition paths and inspection processes.
Static content hidden in documents and procedures. Content not easily navigated, discovered easily referred to efficiently.	Dynamic content that can be easily navigated and published on the portal. Navigation of models by reference links that can easily be published using any proxy technology.
Inconsistency in the format of the safeguards approaches. Process models not commonly used.	Consistent modelling notation. Lingua franca for representing operational aspects. Increased usefulness of process models.
Images, data that can not be processed	Models stored in a repository represent structures that can be queried and searched for. Process structures formalized with PT can be analysed using stochastic techniques.
Knowledge requirements associated to a state level approach not available.	Knowledge awareness through knowledge management models. A link between state level objectives and knowledge requirements. Ability to identify and manage knowledge associated to a specific safeguards approach.
Not easy to share knowledge	Visual representation of models are an effective way of capturing knowledge from domain experts and sharing understanding of issues.
Technology requirements not explicitly documented.	All technology necessary in implementing safeguards can be identified and made explicit. This does not only include equipment but also software, hardware and other tools available to ensure the implementation of the state-level safeguards approach.

Table 7.1. A summary of the benefits introduced by iSMM in the example case

The benefits of the modelling method presented go beyond the ability to generate diagrammatic models out of safeguards related concepts. It offers an environment that provisions easy modelling, publishing and integrating information available in the organization. The content generated represents an evolution of the date-centered culture to a more information based approach. Some of the

benefits of iSMM after its implementation are presented in Teble 7.1. The use of models does not exclude the need of formal documents and procedures however it represents a more effective way organizing information, capturing knowledge and sharing the same within the department.

Conclusion and Future Research

The research question studied is how modelling methods can be used to represent complex processes. Characteristics of such processes are studied based on the example of nuclear inspection. In contrast, these processes require extensive domain knowledge and cannot be acquired off the shelf as it is the case with reference business processes. Knowledge intensity associated to inspection processes is related to the important product resulting from this process, namely the assurance of the peaceful use of nuclear technologies. Ability to perform inspections in a dynamic and unpredictable environment places emphasize on effectiveness over efficiency. The challenge is to capture domain knowledge as it becomes available and efficiently turn it into operations.

The position taken is that for any modelling approach that is meant to capture knowledge from domain experts and translate it to efficient and smart operations three major components have to exist. The ability to a) express the understanding of situations and concepts, b) validate this knowledge by sharing it and finally c) apply the same in processes improvement. Domain specific process models are created, shared and analyzed in order to create effective inspection processes. This descent from domain concepts to tasks performed on daily basis is the main challenge in any model-based approach. A level of formalizm needs to exist in defining the modelling languages in order to process the models created. The approach suggested is to start with easy to use domain specific models created by experts who use them to represent understanding of the subject domain. These models are then used to create operational models that are aligned with operational

objectives. Formalization suggested helps make use of the models not only by humans but also systems.

Throughout the study the principles of modelling were adopted from the breadth of ongoing research in the field. Model Driven Engineering which is more oriented towards software engineering in addition to other frameworks such as Open Models Initiative were considered. The model-based approach presented here was realized with a unique modelling method dedicated to the nuclear verification domain. The technique is enriched with domain specific modelling languages that are used to represent the nuclear fuel cycle in a state as a precondition to the design of effective inspection process models. In order that we add intelligence to the design of inspection processes there is a requirement to formalize domain specific models extending the level of formalism achieved through meta-modelling. The evaluated Pattern Theory was identified as the language that has great potential in formalizing process structures. Moreover, it provisions for probabilistic analysis of process structures named configurations in the theory. Comparison of this formalism with other formalisms such as Petri nets is also evaluated in order to pinpoint the unique properties of this language which shows to strike the optimal balance between user friendly graphical languages and rule-intensive formal languages.

Further research is recommended on the subject of Pattern Theory formalization. The basic concepts of this language were introduced however additional research needs to be performed for building a framework that can achieve the transformation of any model to formal elements of the theory. Similar work was done with graph grammars and petri nets and could be extended to pattern theory. Transformation of the models to patterns and their analysis requires a framework that translates concrete visual language elements to abstract components of the theory. These components can also eventually be transformed to object-oriented structures. Furthermore, an interesting area of research is defining a mechanism to query process structures represented as generator configurations. Similar to the archetypes in the open Electronic Health Records and the Archetypes Query Language. Such a query language can be used to interrogate process structures.

Another area of research suggested is related to objectives-based modelling. A link between modelled high-level objectives and daily activities of the process needs to be further defined. Such a mechanism is required for organizational objectives

to have a considerable impact on the design of processes. Metrics for measuring the compatibility of processes with objectives needs to be established. An interesting application in this area of research would be developing services that use objective models to autonomously identify alternative paths of reaching the same objective.

Glossary of Terms and Abbreviations

Acquisition path analysis - the analysis of all plausible acquisition paths or acquisition strategies for a State to acquire nuclear material usable for the manufacture of a nuclear explosive device [30].

AERO - Aerodynamic Enrichment.

AGR - Advanced Gas-Cooled Reactor.

Aqueous - Type of Reprocessing.

AVLIS - Atomic Vapour Laser Enrichment.

C.A. - Critical Assembly is a form of a research reactor.

CHEMEX - Chemical Exchange Enrichment.

EMIS - Electromagnetic Isotope Separation Enrichment.

EXP - Abbreviation for Experimental Fuel.

FAST - Fast Neutron Reactor.

Integrated Safeguards - the optimum combination of all safeguards measures available to the IAEA under comprehensive safeguards agreements and additional protocols to achieve maximum effectiveness and efficiency in meeting the IAEAs safeguards obligations within available resources [30].

IONEX- Ion Exchange Enrichment.

Gas diff - Gaseous Diffusion Enrichment.

Gas cent - Gas Centrifuges Enrichment.

GCR - Gas Cooled Reactor.

Heavy Water - D_2O Deuterium used as a Neutron moderator.

HTGR - High Temperature Gas Cooled Reactor.

HWR - Heavy Water Reactor.

LWGR - Light-water Graphite-Moderated Reactor.

LWR - Light Water Reactor.

Mining and Milling - Uranium ore is mined and sent to a mill to dissolve it from other materials.

MLIS - Molecular Laser Enrichment.

MOX - Mixed Oxide Fuel. MOX fuel contains plutonium blended with natural uranium, reprocessed uranium and depleted uranium.

NAVAL - Type of Reactor used by the U.S. Navy.

Non-aqueous - Type of Reprocessing.

Physical Model - Physical model of a nuclear fuel cycle a detailed overview of the nuclear fuel cycle used for acquisition path analysis by the IAEA.

PLASMA - Plasma Enrichment.

Post-conversion - sometimes known as Conv2, Conversion 2 or reversion encompasses all chemical transformations subsequent to enrichment or reprocessing in view of manufacturing reactor fuel elements.

Pre-conversion - also known as Conv1 or Conversion 1 encompasses all chemical transformations of nuclear material in order to provide feed material for isotope separation or reactor fuel fabrication.

Safeguards Approach - a set of safeguards measures chosen for the implementation of safeguards in a given situation in order to meet the applicable safeguards objectives. It can be developed for a facility type or state as a whole under Integrated Safeguards [30].

Umet - Uranium Metal. Enrichment of Uranium Metal.

ADOxx documentation of the Modelling Method

B.1 Sample script for the graphical representation of the *Facility* element in the Nuclear Facility Model

=====

GRAPHREP

ATTR "Name" y:.7cm w:c:2.5cm h:t

FONT "Helvetica" h:16.0pt bold color:black

AVAL d1:"Domestic"

IF (d1="No")

 PEN style:dot

ELSE

 PEN style:solid

ENDIF

AVAL t1:"Status"

```

IF (t1 = "Operational")
  FONT "Helvetica" h:7.0pt color:black
  FILL color:yellow
  RECTANGLE x:-1.4cm y:-.7cm w:2.8cm h:1.4cm
  TEXT "Status: " x:-1.16cm y:-0.5cm
  TEXT "OP" x:.1cm y:-0.5cm
  TEXT "Category: " x:-1.16cm y:0.1cm
  ATTR "Description code" x:0.1cm y:0.1cm
ENDIF

AVAL t1:"Status"
IF (t1 = "Decommissioned")
  FONT "Helvetica" h:7.0pt color:black
  FILL color:lightgray
  RECTANGLE x:-1.4cm y:-.7cm w:2.8cm h:1.4cm
  TEXT "Status: " x:-1.16cm y:-0.5cm
  TEXT "CD" x:.1cm y:-0.5cm
  TEXT "Category: " x:-1.16cm y:0.1cm
  ATTR "Description code" x:0.1cm y:0.1cm
ENDIF

```

```
=====
```

B.2 Sample script for the graphical representation of the *Fuel Fabrication* element in the Nuclear Fuel Cycle Model

```
=====
```

```

GRAPHREP

FILL color:lightblue
RECTANGLE x:-1cm y:-.7cm w:3.2cm h:.4cm
FILL color:white
RECTANGLE x:-1cm y:-0.25cm w:0.8cm h:1cm
RECTANGLE x:-0.2cm y:-0.25cm w:0.8cm h:1cm

```

```

RECTANGLE x:0.6cm y:-0.25cm w:0.8cm h:1cm
RECTANGLE x:1.4cm y:-0.25cm w:0.8cm h:1cm
FONT "Arial" h:9pt bold color:black
TEXT "FUEL FABRICATION" x: 0.5cm y:-.7cm w:c:2cm h:t
FONT "Arial" h:9pt color:black
TEXT "U met" x:-.6cm y:.2cm w:c:2cm h:t
TEXT "UO2" x:0.23cm y:.2cm w:c:2cm h:t
TEXT "MOX" x:1.05cm y:.2cm w:c:2cm h:t
TEXT "Exp." x:1.8cm y:.2cm w:c:2cm h:t

```

```

AVAL t1:"U met declaration"
IF (t1 = "Production facility")
  FILL color:lightgreen
  RECTANGLE x:-1cm y:-0.25cm w:0.8cm h:1cm
  TEXT "U met" x:-.6cm y:.2cm w:c:2cm h:t
ENDIF

```

```

AVAL t2:"U met declaration"
IF (t2 = "Research-scale only")
  FILL color:yellow
  RECTANGLE x:-1cm y:-0.25cm w:0.8cm h:1cm
  TEXT "U met" x:-.6cm y:.2cm w:c:2cm h:t
ENDIF

```

```

AVAL t3:"UO2 declaration"
IF (t3 = "Production facility")
  FILL color:lightgreen
  RECTANGLE x:-0.2cm y:-0.25cm w:0.8cm h:1cm
  TEXT "UO2" x:0.23cm y:.2cm w:c:2cm h:t
ENDIF

```

```

AVAL t4:"UO2 declaration"
IF (t4 = "Research-scale only")
  FILL color:yellow
  RECTANGLE x:-0.2cm y:-0.25cm w:0.8cm h:1cm

```

```
TEXT "UO2" x:0.23cm y:.2cm w:c:2cm h:t
ENDIF
```

```
AVAL t5:"MOX declaration"
IF (t5 = "Production facility")
  FILL color:lightgreen
  RECTANGLE x:0.6cm y:-0.25cm w:0.8cm h:1cm
  TEXT "MOX" x:1.05cm y:.2cm w:c:2cm h:t
ENDIF
```

```
AVAL t6:"MOX declaration"
IF (t6 = "Research-scale only")
  FILL color:yellow
  RECTANGLE x:0.6cm y:-0.25cm w:0.8cm h:1cm
  TEXT "MOX" x:1.05cm y:.2cm w:c:2cm h:t
ENDIF
```

```
AVAL t7:"Exp declaration"
IF (t7 = "Production facility")
  FILL color:lightgreen
  RECTANGLE x:1.4cm y:-0.25cm w:0.8cm h:1cm
  TEXT "Exp." x:1.8cm y:.2cm w:c:2cm h:t
ENDIF
```

```
AVAL t8:"Exp declaration"
IF (t8 = "Research-scale only")
  FILL color:yellow
  RECTANGLE x:1.4cm y:-0.25cm w:0.8cm h:1cm
  TEXT "Exp." x:1.8cm y:.2cm w:c:2cm h:t
ENDIF
```

```
AVAL t9:"U met potential inconsistencies"
IF (t9 = "Yes")
  FILL color:red
  POLYGON 3 x1:-0.68cm y1:-0.23cm x2:-1cm y2:0.1cm x3:-1.0cm y3:-0.23cm
```

ENDIF

AVAL t10:"UO2 potential inconsistencies"

IF (t10 = "Yes")

FILL color:red

POLYGON 3 x1:0.11cm y1:-0.23cm x2:-.21cm y2:0.1cm x3:-.21cm y3:-0.23cm

ENDIF

AVAL t11:"MOX potential inconsistencies"

IF (t11 = "Yes")

FILL color:red

POLYGON 3 x1:0.92cm y1:-0.23cm x2:.6cm y2:0.1cm x3:.6cm y3:-0.23cm

ENDIF

AVAL t12:"Exp potential inconsistencies"

IF (t12 = "Yes")

FILL color:red

POLYGON 3 x1:1.72cm y1:-0.23cm x2:1.4cm y2:0.1cm x3:1.4cm y3:-0.23cm

ENDIF

AVAL t13:"Referenced nuclear process"

IF (t13 <> "")

FILL color:white

ELLIPSE x:-.90cm y:-0.90cm rx:0.1cm ry:.1cm

FILL color:black

ELLIPSE x:-.65cm y:-0.90cm rx:0.1cm ry:.1cm

FILL color:white

ELLIPSE x:-.40cm y:-0.90cm rx:0.1cm ry:.1cm

ENDIF

IF (t14 = "")

ATTR "Name" x:0.5cm y:1cm w:c:3cm h:t

ELSE

ATTR "Referenced nuclear process" x:0.5cm y:1cm w:c:3cm h:t format:"%m"

ENDIF

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