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SELECTED ISSUES OF SYSTEMS ENGINEERING METHODOLOGY IN THE DESIGN OF TRANSPORT SYSTEMS

Summary. *The selected issues of system engineering methodology in the design of transport systems have been presented. The discussed methodological issues were presented in the example of the metropolitan railway concept project. The system description of the transport project is introduced in accordance with the principles used in systems engineering. The presented case study concerns the methodology of designing the concept of the railway transport system. In the proposed case study, the main issue was the development of a document called the Concept of the Metropolitan Railway System (CoMRS) in the urban area of the Metropolis called in Poland GZM. It was assumed that this document would be a system document developed with the use of Systems Engineering methods in order to build, implement and develop a modern complex railway transport system covering the urban area of the GZM Metropolis. Therefore, in the first place, an additional but essential document was developed – the Methodology for the Metropolitan Railway System Concept (MoCoMRS), which contains a comprehensive methodological description of how to proceed with the use of Systems Engineering methods required for the development of the CoMRS. The methodological guidelines relating to the V model were presented in detail. The methodology description also took into account the system life cycle model in the perspective of the enterprise and systems engineering using the V model. When applying systems engineering in the design of transport systems, it is proposed to use this model, which organizes the system procedure during the design process. The guidelines regarding the use of this model and the application of systems engineering methods for CoMRS, relating, inter alia, to the following design stages: system assumptions, system requirements, high-level design, detailed design, were formulated. The case study of the concept of metropolitan railway presented in this paper is based on a real transport project, and the current stage is working on the preliminary feasibility study of this railway system. It is very important, because it is possible to verify and iteratively correct and update the methodology of designing this railway system depending on the changing conditions and criteria resulting from, among others, different stakeholder aspirations that shape the system requirements. This procedure was also included in the V model in phases of development, construction and implementation of the system, as well as in phases of integration, verification and validation of elements and the entire railway system.*

Key words: *transport systems, systems engineering, V model, metropolitan railway, methodology, transport project.*

1. INTRODUCTION

Presentation of practical issues related to the application of Systems Engineering is desirable as it enables the identification and discussion of good and bad practices. It also creates the possibility of introducing new practical solutions and, on their basis, developing new theories, methods and tools, which are first verified and validated in individual cases and then modified to generalize their application to similar cases in a given field and then to cases analogous to others fields of engineering practice.

This paper presents selected issues of the system engineering methodology used in the design of transport systems – a case study of the metropolitan railway concept. The presented scope covers the key system issues when applying the V Model of Systems Engineering in the practice of designing a new, complex transport system, i.e. the metropolitan railway.

The structure of this paper is as follows. The second section presents the problem of statement in literature review. Then, in the third section, the purpose and scope of the presented issues were presented, as well as literature containing a detailed discussion of selected key issues of the presented project. This literature complements and extends the discussion of the application of systems engineering in an exemplary project on rail transport. In the fourth, fifth and sixth sections, the following are discussed: the assumptions of the methodology in the presented case study, the characteristics of a transport project in relation to systems engineering, and the V model as a tool in the methodology of systems engineering for transport projects. The article ends with conclusions and future research perspectives.

2. PROBLEM STATEMENT AND LITERATURE REVIEW

The issues presented in this paper relate to the methodology that uses systems engineering in the design of transport systems. The issues were presented in terms of engineering practice, i.e. a case study on a new railway transport system serving the transport needs of the urban metropolis area was used in the discussion. The rationale for a such topic and the scope of the content of this paper is a literature review. It was carried out in relation to the principles and practice of applying systems engineering, the application of systems engineering in design and the entire life cycle of transport systems, defining the purpose and scope of systems engineering and design methodology transport systems using systems engineering. In particular, the needs and scientific benefits of presenting case studies of applying systems engineering in various fields were highlighted, which underline the relevance of the topic presented in this paper.

The monograph [1] presents the principles and practices for those who want to think like system engineers. Several models are presented there. They include a hierarchical model of complex systems, a system life cycle model derived from existing models but more explicitly related to evolving engineering activities and participants, a model of steps in the systems engineering methods and their iterative application to each phase of the life cycle, a concept of "materialization" with stepwise evolution of an abstract concept to an engineered, integrated, and validated system, and along with discussing the specific responsibilities of systems engineers that evolve over the life of a system and the knowledge of a system engineer to be able to perform them effectively.

The application of Systems Engineering in the area of transport systems [2] is very well developed in ITS, i.e. Intelligent Transport Systems. In the underlying ITS design documentation [3-6], such systems are defined as follows: ITS means electronics, communications, or information processing used singly or in combination to improve the efficiency or safety of a surface transportation system. And in this area of transport, Systems engineering is a structured process for arriving at a final design of a system [7]. The final design is selected from a number of alternatives that would accomplish the same objectives [8, 9] and considers the total lifecycle of the project, including not only the technical merits of potential solutions but also the costs and relative value of alternatives [3, 4].

One of the many basic advantages of the application of systems engineering, in particular concerning work in a multidisciplinary project team, the authors indicate in [10] as follows "The specialist engineer is well served with textbooks, which cover many of the subsystems in detail and in-depth. He is unlikely to learn very much about his own specialist topic from this book [10]. But he may well learn something about other specialists' disciplines, and, it is hoped, enough for him to appreciate the trade-offs that affect his own subsystem in relation to others".

The need for a holistic approach to the design of transport systems, in this case rail transport, is also indicated by the author [11], who states that the purpose of this publication is 'to develop an understanding of the engineering concepts involved, for all disciplines, in the planning, design, construction, equipping, maintenance and renewal of all types of railway'.

The advantages and benefits of using systems engineering are also emphasized by the authors [12]. The U.S. Department of Defense and the defense industry indicate that applying systems engineering throughout the system lifecycle improves project performance, as measured by a project's ability to meet technical requirements within cost and schedule constraints [12].

The monograph [13] presents the method of shaping traffic in urban transport networks with the use of Systems Engineering that enables the preparation and implementation of system-relevant solutions, reduces congestion in transport networks of cities and enables their sustainable development towards smart sustainable cities. This method, using system engineering, takes into account the comprehensive approach to the problem of traffic shaping in urban transport networks, by using models [14], methods and tools appropriate to identification of the area and environment in which the problem occurs, diagnosis of the condition in terms of factors and processes affecting the problem, defining the problem in terms of quantity and quality [15]. After elaborating the above-mentioned issues, the method enables the selection of appropriate activities / instruments in the form of functional configuration, taking into account technical and organizational options, preparation and implementation of an appropriate project, using systems engineering, which enables solving a defined problem by implementing the appropriate variant of functional configuration, using the V model as an appropriate tool in the field of systems engineering.

The library of case studies [16], developed by The International Council on Systems Engineering (INCOSE), presents several transport case studies. The presentations include only a synthetic description of the cases in the context of keywords, background to the project, description of the challenges faced, description of the systems engineering performed, outcomes, and conclusion. However, despite such short descriptions of projects, INCOSE points to the benefits of such case study review. I.e., there is a need on the part of practicing systems engineers for a library of case studies of the application (or sometimes the lack of application) of Systems Engineering to transportation projects in order to learn from the experiences of others and to make a case for investing in Systems Engineering. Moreover, as this library grows, there will be clear topics that the reader can perceive and use in their own project, even if it differs in some important respects from the projects described in the case study library.

The approach to applying Systems Engineering in practice, based on the presentation of case studies, is also indicated by NASA in [17], which describes the best systems engineering practices to be considered when developing and implementing NASA programs and projects large and small. It provides a generic description of Systems Engineering as it should be applied throughout NASA. The engineering of NASA systems requires a systematic and disciplined set of processes that are applied recursively and iteratively for the design, development, operation, maintenance, and closeout of systems throughout the life cycle of the programs and projects. The scope of this handbook includes systems engineering functions regardless of whether they are performed by a manager or an engineer, in-house or by a contractor [17]. And then the goal of this handbook is to increase awareness and consistency across the NASA Agency and advance the practice of Systems Engineering.

Contemporary continuous and dynamic development of IT systems in the field of automation and control in transport, including rail transport, requires systems engineering to use mathematical system modeling tools to test and verify the operation of IT systems. This is very important because most software errors cannot be corrected by testing (as the computer scientist, Edsger Dijkstra remarked: "Testing (software) shows the presence, not the absence of bugs") the software and fixing the failures in the way that mechanical systems and structures can be tested and fixed. It is because digital systems are so complex that testing every state that could contain an error would take an impractical amount of time and resources

[18]. In the context of railway systems engineering, system verification is of major importance as software failures can cause serious damage [19]. Therefore, Model-Based Systems Engineering (MBSE) enables system development and analysis on a suitable level of abstraction [20]. MBSE, already standard practice in domains such as defense and aerospace engineering, is also gaining popularity in the railway domain, where MBSE tools are used to create a standardised system architecture [21].

The challenge of enabling both high-level system modelling and formal system verification is addressed by employing Systems Modeling Language (SysML) [22], widespread systems modelling language, and Event-B [23], formal systems modelling language particularly suited for automated system verification [19]. The second primary area of systems design is the lifecycle of the system, for which The Lifecycle Modeling Language (LML) is used. The LML has been developed to provide an extensible language that includes both visualization models and an ontology. When LML is combined with a SysML, a modeling framework is created that supports systems engineering processes across the spectrum of lifecycle issues better [24].

Model-Based Systems Engineering (MBSE) is also used in the automotive field. In [25], the authors present the application of MBSE to early identification of validation problems from the stakeholder perspective, which they use to systematically design tests that lead to scenario-based modeling and automated system requirements analysis. The decomposition of stakeholder requirements into system requirements is part of the requirements analysis phase, which results in the specification of system requirements – a key boundary document for further activities related to system design and validation. This study [25] confirms that the MBSE-based methodology is applicable and improves existing test specification requirements and processes by supporting integrated and stakeholder-focused product modeling and validation systems.

Systems engineering distinguishes between two concepts of “requirements” – a stakeholder requirements specification (StaRS), and a system requirements specification (SysRS). The term StaRS describes a “structured collection of the requirements (characteristics, context, concepts, constraints and priorities) of the stakeholder and the relationship to the external environment” [26]. Whereas the term SysRS is used as a collection of requirements that describe “what the system needs to do, how well, and under what conditions, as required to meet project and design constraints” [27]. The SysRS includes different types of requirements: functional, behavior, performance, interface, fault and failure handling requirements etc. The specification and analysis of SysRS include a requirements analysis phase to transform the defined StaRS into a set of SysRS that will guide the design of the system. In this process (often a predominantly manual process [28]), requirements are analyzed for correctness and verifiability, and ensures consistency and two-way traceability between system requirements and stakeholder requirements [29-33].

3. PURPOSE AND SCOPE OF THE PRESENTED ISSUES

In the development of the concept of a new transport system covering the metropolitan area, tools and methodology in the field of systems engineering were used. Systems Engineering is a field of applied research, defined as “the science of creating complex systems in order to guarantee the most effective design, matching, testing and operation of all subsystems that constitute them” [34].

Based on the literature review in the previous section of this paper on the application of Systems Engineering in the practice of transport projects, it turns out that publications in this area are still desirable. It is due to the properties of Systems Engineering, an engineering science based, among others, on discussing good and bad practices. It is practically impossible to present the entire project on designing a complex transport system in one paper. Therefore, the aim of this paper is to present selected issues of system engineering methodology in the design of transport systems – a case study of the concept of metropolitan railway. However, the other key aspects of this project, which complement and extend the content of this paper, the reader will find, among others, in [35] – in terms of the possibility of using telematics applications in the metropolitan railway, [36] – systemic characteristics of the metropolitan railway concept project, [37] – the way of variants of the metropolitan railway concept at the stages of constructing high-level and detailed projects as examples of variants of areas, [38] – the role of stakeholders in the process of designing the concept of the metropolitan railway.

4. ASSUMPTIONS OF THE METHODOLOGY IN THE PRESENTED CASE STUDY

It was assumed that the term methodology should be understood as a clearly defined, reliable system of methods, rules and research procedures that allow for the development of a given issue. In the presented case study, the main issue was the development of a document – the Concept of the Metropolitan Railway System (CoMRS) [39] in the area of the Metropolis, called in Poland GZM, with the characteristics of an Urban Conurbation. It was assumed that the CoMRS would be a system document developed with the use of Systems Engineering methods to build, implement and develop a modern complex railway transport system covering the area of the GZM Metropolis in Poland. Therefore, in the first place, an additional but essential document was developed – the Methodology for the Metropolitan Railway System Concept (MoCoMRS) [40], which contains a comprehensive methodological description of how to proceed with the use of Systems Engineering methods required for the development of the CoMRS. These two system documents are supplemented by the third document – the Preliminary Feasibility Study of the Metropolitan Railway (PFSoMRS). The mentioned three interrelated system documents, together with the target transport system, are presented in Fig. 1.

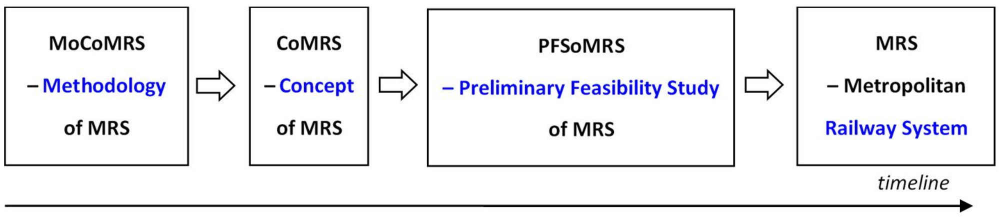

Fig. 1. Three interrelated system documents together with the target transport system [40,41]

The system of actions, which makes up the quasi-cycle of modification procedure, presented in Fig. 2, was used twice during the presented case study. First, the system of actions was used to design the Methodology of MRS (MoCoMRS) – treating the MoCoMRS document in a systemic way. Therefore, in the diagram in Fig. 2, the designation "Transport Project" should be referred to "MoCoMRS" while other conceptual documents and experience of the author's team were used as "DESIGN METHODOLOGY". Then the system of actions and the developed document "MoCoMRS" as "DESIGN METHODOLOGY"were used again to develop the document Concept of the Metropolitan Railway System (CoMRS). In this case, the designation "Transport Project" should be referred to "CoMRS" in the diagram in Fig. 2. The comprehensive interpretation of the diagram is as follows:

a) the following systems take part in the cycle: TEST&RESEARCH SYSTEM, DESIGN SYSTEM, PRODUCTION SYSTEM, OPERATING SYSTEM, USAGE SYSTEM;
b) the USAGE SYSTEM generates a need formulated as the question "how to instrument an action to achieve the goal?";
c) the need is transformed by the INTERPRETER into a design/project problem, which in its general form is written as the question "what and how to use to achieve the goal?";
d) the DESIGN SYSTEM generates a cognitive need and a cognitive problem for the TEST&RESEARCH SYSTEM (Transport Project), because solving the problem requires getting to know reality and knowing the criteria for evaluating actions;
e) the cognitive need concerns both substantive issues and procedural issues concerning the entire DESIGN SYSTEM with DESIGNING Transport Project, therefore an appropriate research methodology for this system may be necessary;
f) problems formulated in the questions "what and how to use?", "how to exploit it?", and "how to make it?" are solved during DESIGNING process;
g) the result of solving a design problem is a SYSTEM DESIGNED Transport Project containing, inter alia, the following directives concerning the subject of the project, i.e. "THIS IS WHAT CAN BE CREATED", "THIS IS WHAT CAN BE EXPLOITED", "THIS IS WHAT CAN BE

USED", and the design process "This is HOW to MAKE IT", "This is HOW to EXPLOIT IT", "This is HOW to USE IT";

h) on the basis of the SYSTEM DESIGNED Transport Project, activities are performed consisting in the PRODUCTION SYSTEM – static implementation, i.e. a ready system, but not yet functional, e.g. a new railway line has been built;

i) dynamic implementation in the OPERATING SYSTEM – in accordance with the principles of operation specified in the DESIGNED Transport Project – it is a system operating in a ready-to-use condition, i.e. HANDLED Transport Project, e.g. starting trains on a constructed railway line;

j) the last stage of the cycle consists in the fact that the generator of the need – the USAGE SYSTEM with USER Transport Project starts the use of the system, carrying out activities that achieve the goal and thus satisfies the need, e.g. transporting passengers by trains on a constructed railway line.

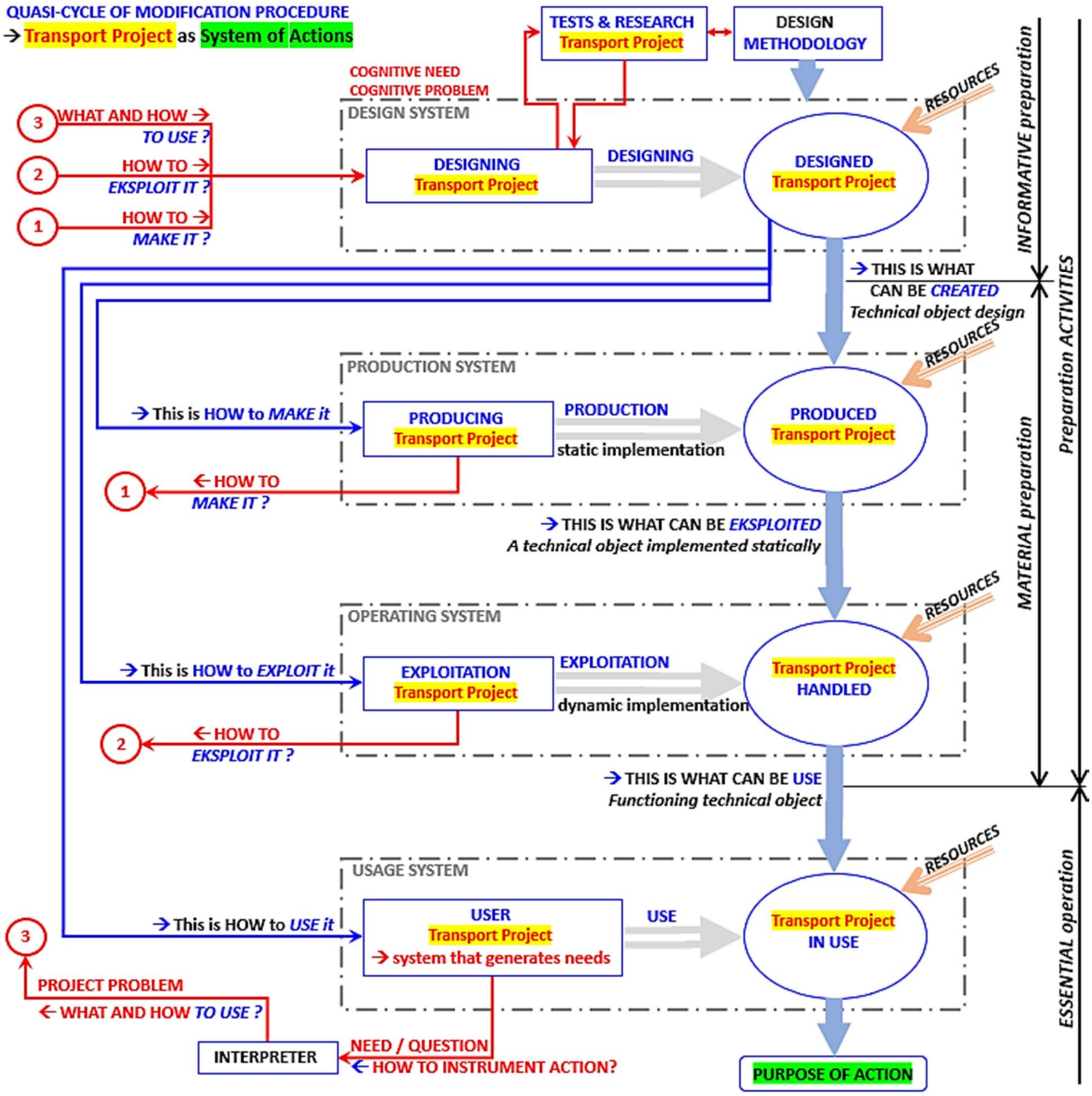

Fig. 2. The system of activities consisting of a quasi-cycle of modification proceedings [13, 42]

5. CHARACTERISTICS OF TRANSPORT PROJECT IN RELATION TO SYSTEMS ENGINEERING

The result of preparing a transport project in accordance with the engineering of transport systems should be a modern transport system adapted to the current and, above all, future requirements and needs. Therefore, transport is considered as a system in which the way of solving problems focuses on the whole issue (holistic approach) and not only on its individual elements. The transport system is therefore a deliberate set of specific components and relations between them and is characterized by the following features and principles specific to the systems [13, 34]:

- the transport system has a specific structure consisting of subsystems and simple elements connected with each other by a network of mutual relations,
- in the transport system, there are various interactions / relationships of the elements of this system on its entirety and between its individual elements; the form of these relationships is referred to as the structure of the transport system (it may be, for example, a hierarchical or network structure); in this structure, a holistic perception of transport processes is observed, including synergy effects,
- transport systems have a dynamic nature manifested in specific activities resulting from the objectives and tasks pursued by a given system, while these activities are variable in time and depend on the changing conditions in the transport system itself (e.g. changing demand for transport in time, variable in time load of the transport network, etc.), as well as in the environment of this system;
- the set of elements and interrelationships of the transport system are of particular interest, as they can be changed to adapt to newly formulated goals (e.g. changing the timetable or changing the location of train stops in order to meet new transport needs generated in the socio-economic system),
- transport systems pursue their goals and tasks, therefore the creation of such system should begin with the formulation of these goals; some of these goals should result from the subjective aspirations of various stakeholders of such transport system and from objective requirements – e.g. requirements resulting from technological and environmental constraints, etc.,
- transport systems can be divided gradually by distinguishing subsystems, which are systems in themselves, and elements constituting the smallest (elementary) parts of the system; these are procedures within the framework of systemic decomposition and system analysis; during such proceedings, it is necessary to identify the interdependencies between the distinguished subsystems, which become the conditions, constraints, or boundary conditions in the system analysis, and then enable the construction of the entire system at the stage of system synthesis / subsystem aggregation,
- transport systems as well as subsystems and elements of these systems have specific attributes expressing their qualitative and quantitative states; these are, for example, such attributes as the volume of passenger flows determining the organization of railway transport, transport availability, the technical condition of transport infrastructure now and in a planning perspective, and the quality of transport services described by specific parameters, e.g. travel time, delay in relation to the timetable, etc.,
- transport in the system description has its environment, which consists of everything that affects the functioning of transport systems or the results of transport systems operations, and at the same time the elements of the environment are not elements of transport systems,
- transport systems, including their subsystems and simple elements perform their tasks and achieve goals by processing input into results during a given process, whereby
  - input:
    - input can take the form of material and intangible resources as well as steps necessary for the transport system to function and fulfill the assigned tasks and achieve goals,

        - input should be controllable and monitorable,
        - input can be a feedback in the transport system itself,
    - process:
        - process is a series of actions in specific sequences by which the system physically transforms input into outputs,
        - process has, among others, the following desirable attributes: fulfills the tasks of the transport system, effectively achieves the expected results, minimizes the consumption of the input and harmful effects,
    - output/results:
        - the results are the effects of the functioning of the transport system,
        - the results are diversified: the desired results contribute to the achievement of the goals of the transport system, undesirable or harmful results hinder the achievement of goals and / or have a negative impact on the surroundings of the transport system, neutral results – they do not affect the achievement of the goals by the transport system.
- transport systems have various constraints that make it difficult to achieve goals and get things done; in transport systems there may be conflicts between the tasks of individual components of their structure, which negatively affects the functioning of the entire transport system,
- the operation of all components of the transport system should be coordinated, and then the transport system that achieves the assumed goals and meets the requirements during coordinated work is referred to as an integrated transport system,
- transport systems may be open systems and then when creating them, relations with the environment should be taken into account, or transport systems may be closed systems, i.e. functioning independently and autonomously, not requiring connection with the environment.

6. V MODEL AS TOOL IN THE METHODOLOGY OF SYSTEMS ENGINEERING FOR TRANSPORT PROJECTS

When applying systems engineering in the design of transport systems, it is proposed to use the so-called the V model, which organizes the system procedure during the design process. At the same time, the following aspects of transport systems engineering are recommended to be used in the design process [1, 3, 17, 34]:

- multidisciplinary project team:
    - it is a team that performs multifunctional, interdisciplinary, simultaneous work,
    - this team works with stakeholders of the transport system being designed, with the main stakeholders being operators, end-users, and transport system designers,
    - designers belonging to the design team (design and construction of the transport system) cooperate with the users of the designed system (operation and maintenance of the system) and the beneficiaries of this system (they finance the system and own it),
    - the transport system design team determines the following issues in contacts with other stakeholders:
        - needs / aspirations that the system should fulfill,
        - based on the needs / aspirations, system requirements are formulated that define the usability of the system, i.e. what exactly the system should implement,
- structure, elements and modularization of the designed transport system:
    - covers the functional and physical construction of the transport system,
    - elements and subsystems are designed in such a way as to fulfill the functions necessary to achieve the goals and to meet the aspirations and requirements of the stakeholders of the designed transport system,

- o one of the basic priorities in designing the functionality of the transport system is to meet the aspirations and requirements of the stakeholders, taking into account technological, legal and environmental conditions.

– transport system life cycle, which means taking into account all phases of this cycle in the work related to its design (see Fig. 3),

– the life cycle of the transport system from the project / company point of view – includes management-oriented stages in which, among others, investment decisions on whether the transport system should move to the next stage (preliminary studies, feasibility studies, implementation, retirement) or whether it should be modified, canceled or withdrawn; taking into account decision criteria regarding risk, costs, schedule, functionality etc.; the project / enterprise point of view concerns not only the entire transport system being the subject of the project, but also its subsystems and elements that are components of the structure of this system; subsystems and components may have a shorter lifetime than the entire transport system in which they are embedded and, during the lifetime of the entire transport system, may require modification,

– transport system life cycle from a systems engineering point of view – systems engineering is first used to develop technological or simulation (virtual) prototypes in the concept phase, including preliminary research and feasibility studies; then, in the development phase, a system prototype and a pre-production prototype are developed; in the construction, use and maintenance phases, systems engineering is used in modification (redesign) processes when undesirable and unexpected changes occur, for example, due to design errors or failures, or the need to take into account new requirements caused by changes in technology, or expected threats to the functionality of the transport system.

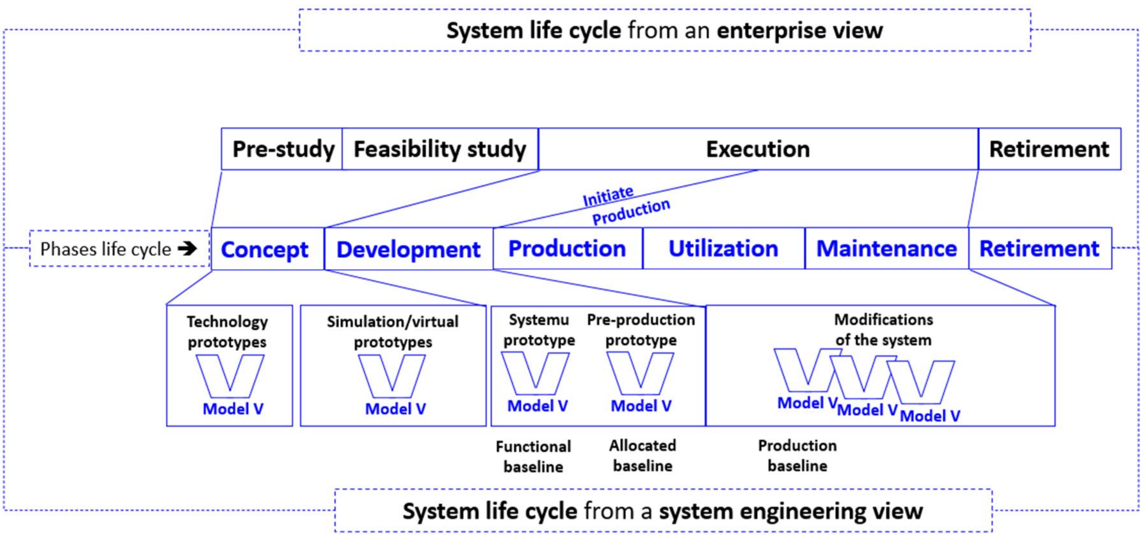

Fig. 3. System life cycle model in the perspective of the enterprise and systems engineering using the V model [43]

In the Methodology for the Metropolitan Railway System Concept (MoCoMRS) [40, 41], guidelines regarding the V model (Fig. 4) and the application of systems engineering methods, were formulated relating, inter alia, to the following design stages:

– stage of system assumptions,
– system requirements stage,
– high level design stage,
– detailed design stage,
– phases of development, construction and implementation of the system,
– phases of integration, verification and validation of elements and the entire system.

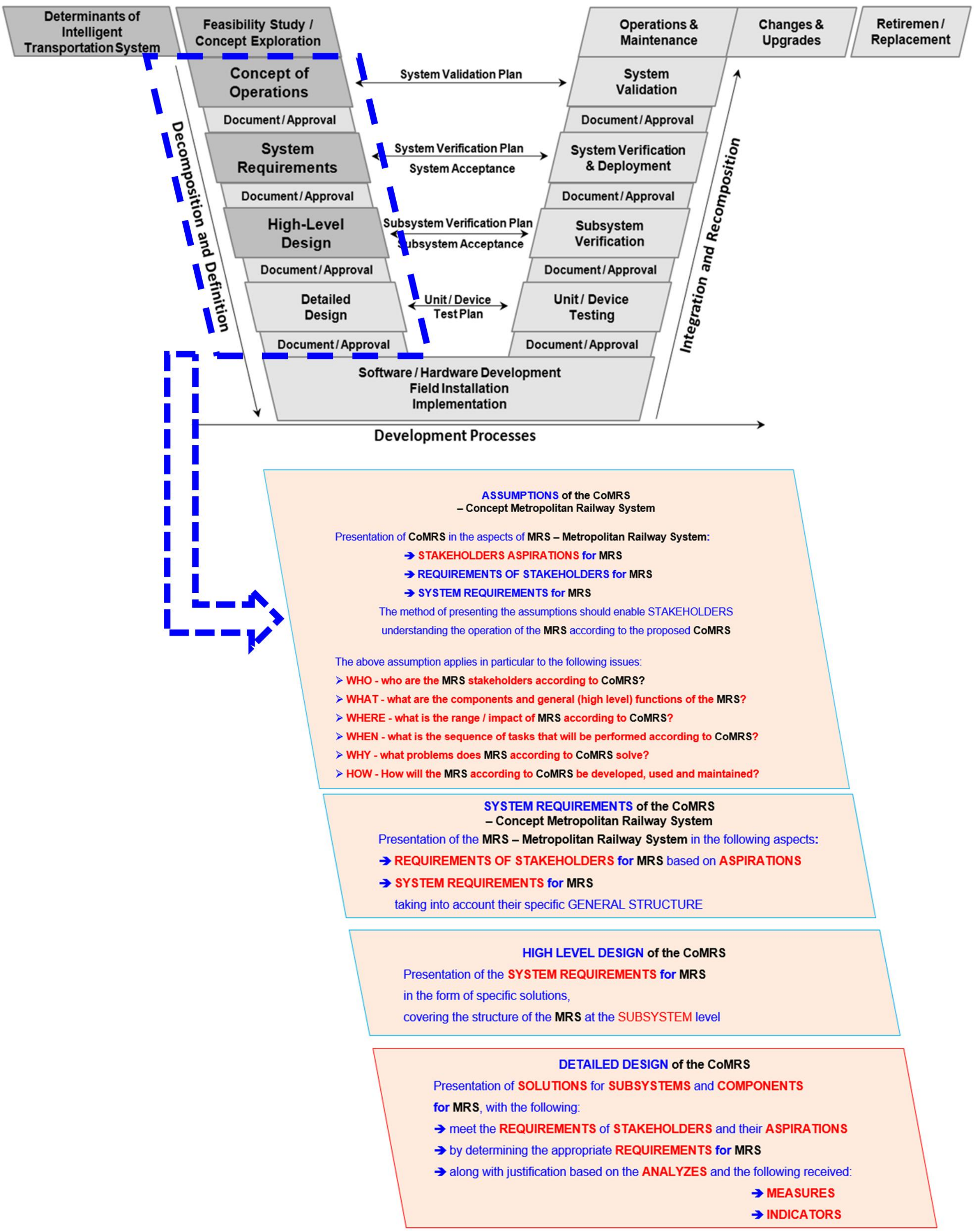

Fig. 4. Mapping the process of designing the Metropolitan Railway system in the V model in Systems Engineering [13, 40, 41]

The guidelines for the V model at the level of system assumptions were formulated as follows [40]:

– the assumptions of the system are to provide all stakeholders with knowledge about the two systems being designed in an understandable way: the concept of the Metropolitan Railway, and in this concept – the Metropolitan Railway system in terms of operation, maintenance and development;

- the assumptions of the system should be the basis for the system requirements and subsequent, more detailed stages of building the Metropolitan Railway system, but these assumptions should not contain requirements so detailed as to indicate specific technical and technological solutions, because various alternative solutions regarding the planned Metropolitan Railway should not be excluded on this stage of the V model;
- documentation of the system assumptions should be prepared both in text and graphical form in a comprehensible, accessible and appropriate way for all system stakeholders, and at the same time the documentation must be detailed enough to be used for changes and updates of the system in the iterative design of the Metropolitan Railway Concept and throughout the life cycle of the Metropolitan Railway system.

The guidelines for the V model at the system Requirements Stage were formulated as follows [40]:

- formulation of system requirements for complex systems, such as the Concept treated as a system document and the target of this Concept, i.e. the Metropolitan Railway system; the complexity of such system is due to, inter alia, many stakeholders, sometimes with conflicting interests / aspirations; the formulation of system requirements should be characterized by their very careful definition, because making mistakes at this stage causes problems with determining the dependencies between parts of these systems; the correct formulation of system requirements is a condition for the system to meet / implement the requirements of all stakeholders,
- formulation of system requirements for the entire designed transport system depends on the solution of the following issues:
  - estimation of labor and time consumption,
  - quality assessment of the proposed system requirements,
  - working out compromises in relation to conflicting stakeholder requirements,
  - quick response to changing requirements.

The guidelines for the V model at the High-Level Design Stage were formulated as follows [40]:

- High-Level Design Stage presents the general structure of the designed transport system, distinguishing all essential components (parts) of the system – subsystems and their elements, and the relations between them; however, it is possible / advisable to use many different ways of dividing the designed transport system into components, resulting from the specificity of this system and its subsystems in terms of organization, equipment, technology, functionality, etc.,
- each system component in the High-Level Stage should be defined in terms of functionality and performance, with particular emphasis on its interfaces with external systems and other components,
- design at the High-Level Stage should be iterative, taking into account, inter alia, the following tasks:
  - the task of proposing several mutually alternative transport systems in the High-Level Stage and their comparison, among others in terms of performance, reliability, cost and other criteria, and an indication of a recommended project,
  - the task of evaluation of proposed mutually alternative transport systems according to specific criteria:
    - specified selection criteria, the analyzes prepared and the results obtained, indicating the recommended transport system among the assessed alternatives, should be documented,
    - if among the proposed alternative transport systems their assessments are the same or similar, then these alternatives should be assessed by stakeholders,
  - the task of aspiration analysis and formulating of system requirements:
    - analysis of aspirations and formulation of system requirements are necessary to assign them to the subsystems and components of the designed transport system in the High-Level Stage, because, on this basis, the specific objectives of individual subsystems and

components of the designed transport system are formulated, as well as the purpose of the entire system,
    - assigning system functional requirements and related performance requirements to the subsystems and components of the designed transport system,
    - the relationships between the required functions of the designed transport system and its subsystems and components are analyzed in detail in the process of formulating system requirements; in this way, each component of the system being designed is as independent as possible from other components,
  - the task of preparing a description of interfaces between systems:
    - descriptions for external interfaces, i.e. the interfaces between the designed transport system and external systems,
    - descriptions for internal interfaces in the designed transport system, i.e. interfaces between subsystems and components of the designed system,
    - assessment of each interface to determine which standards are relevant, which standards should be implemented and which standards perhaps should be introduced gradually – as part of long-term plans,
    - preparation of documentation, among others, in terms of the type of data, data format, range of values and frequency of information exchange in individual interfaces.

The guidelines for the V model at the Detailed Design Stage are as follows [40]:

- Detailed Design should include a full specification of the components that make up the transport system, specify how the components will be developed to meet the system requirements, and specify detailed design activities for ready-made standard components (procured) and for non-standard components (designed),
- Detailed Design is an iterative process in which, among others, the following tasks:
  - selection of ready-made components – those that will be purchased,
  - development of prototypes of designed components,
  - development of detailed specifications for individual components,
  - review of detailed projects of each component in terms of ensuring the achievement of the assumed goals and adopted system requirements,
  - project team coordination meetings and periodic, regular or ongoing reviews to monitor progress and solve problems, integrate concurrent design activities and mitigate possible future risks when integrating transport system components,
  - consultation of the design team with stakeholders to review and approve the elements of the detailed design before the implementation team starts building the transport system,
  - preparation of project documentation for the entire transport system,
- Detailed Design of the transport system should take into account many different factors related to satisfying the various aspirations of stakeholders, which requires an optimal balance between the parameters characterizing these factors; functional design should therefore take into account the following objectives:
  - functional design, i.e. taking into account the functional potential and system performance – so that the designed system can carry out tasks that will ensure the achievement of the planned goals,
  - design taking into account the specific reliability of the transport system operation,
  - designing with regard to maintaining the efficiency of the system (maintenance) – minimizing such factors as service time, resources involved and costs of maintaining the transport system,
  - designing taking into account the human factor – ergonomic aspects, the optimum of the human-machine system,

  - designing taking into account the technology of activities / tasks – minimizing resource requirements,
  - designing with regard to economic feasibility – the goal is to minimize costs throughout the life cycle of the transport system and its subsystems and components, not just the costs of creating the system,
  - designing with consideration of social acceptance – the transport system as an acceptable part of the social system.

The guidelines for the V model at the stages of Development, Construction and Implementation of the system are [40]:

- ensuring the proper functioning of the transport system (fourth phase of the system development cycle) requires the consideration of the entire life cycle of the transport system,
- taking into account the principle that the system is not the end product of the project (operation), but begins to function after its implementation in the transport system development cycle,
- the transition to the stages of construction and implementation of the transport system may take place only after the detailed design has been approved for implementation,
- during the construction (production) of the transport system, it is important to compare the planned results with the actual results and take possible corrective actions,
- during the construction of the transport system, the work carried out should still be assessed,
- during the transport system implementation phase, there is a need to carry out tests of the target system – they are performed by teams of designers, contractors, users and other stakeholders,
- implementation of the transport system is a process consisting in handing over the system to users and stakeholders, which should be properly planned at an early stage of the system implementation – so that its implementation takes place at the latest at the end of the system production,
- after completing the implementation of the transport system, provide users and / or stakeholders with appropriately prepared materials for their training in the operation and maintenance of the system.

The guidelines for the V model at the stages of Integration, Verification and Validation of elements and the entire system are as follows [40]:

- the procedure during the integration stage includes the verification of individual components and then their integration into subsystems – verification is a confirmation that the system meets the adopted system requirements and, in practice, consists in the use of the following methods:
  - a test which is a direct measurement of the performance,
  - demonstration, i.e. observation of the operation of a component / system in an expected or simulated environment,
  - inspection, which is a direct observation of the achievement by a component / subsystem of system requirements,
  - analysis using logical, mathematical and graphic methods,
- the order of integration of components into subsystems results from the integration plan, which includes phased testing and verification with the use of tools defined in the verification plans of elements, subsystems and the entire transport system, while the use of specific testing tools, including simulation models, requires careful verification of these tools before being used to test system components,
- in the course of each verification case, all actions and system responses should be recorded and analyzed, e.g. for adoption an appropriate mode of possible repair, correction or modification of the transport system,
- integration is carried out until the design or construction of the transport system is positively verified and integrated, and this activity may require the involvement of various groups of stakeholders; additionally, the verification activities should not be limited – the correct schedule

for carrying out these activities and their proper scope are necessary to identify system defects at an early stage of the integration process,

- the verification processes should be carefully documented, including integration plan, verification plan with test procedures, traceability matrix of activities for components and subsystems, documentation of integration tests and their results; the documentation should contain an updated description of the activities that were performed and their results regarding the compliance of components, subsystems and the entire transport system with system requirements,
- validation of the system confirms that the integrated and verified system is possible to build and that, once implemented, it will meet all the requirements of the stakeholders – it will be fully useful for them; a system that has passed all stages of verification is validated; the validation process allows the owner / operator of the system to make sure that it operates in accordance with the requirements of stakeholders, defined at the stage of system assumptions,
- the validation process should be carried out in accordance with the system validation plan developed and updated as needed, and its results should be carefully documented,
- the system implementation phase begins a transition process that requires monitoring and evaluation based on the results of acceptance tests that confirm that the transport system is operating as intended in its real environment; after the transition period – after the implementation process – the transport system is fully operational.

7. CONCLUSIONS AND FUTURE RESEARCH PERSPECTIVES

The selected issues of system engineering methodology in the design of transport systems based on a case study of the concept of metropolitan railway presented in this paper are based on a real transport project, the current stage of which is work on the preliminary feasibility study of the planned metropolitan railway system. This is very important because, in the work on actually implemented projects (and not design simulation), it is possible to verify and iteratively correct and update the methodology of designing a specific system depending on the changing conditions and criteria resulting from, among others, different stakeholder aspirations that shape the system requirements.

This is particularly evident in the case of changes in the aspirations of stakeholders already reported during the ongoing stages of system design, which results in the need to redefine the system requirements and even the functional scope of the designed system and its subsystems and components. Such disruptions and changes in the project can and do occur, especially when there are many stakeholders-beneficiaries-local authorities with different particular and contradictory aspirations. Such situations also took place in the discussed case study because in the metropolitan area for which the metropolitan railway system was designed, there are many stakeholders who are the authorities of local government units, i.e. cities and towns that are part of the metropolis. Discussions on often contradictory aspirations occurred when consulting the results of project work at subsequent stages in the V model. Such disruptions in the project require specific interdisciplinary knowledge from the project team– also in the field of psychology, negotiation, education, presentation and interpersonal contacts.

Therefore, another paper is planned to present the interdisciplinary aspects of the project team in the context of the analysis of the aspirations of many stakeholders representing local authorities of cities and towns from the common area in which the transport system is designed.

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ОБРАНІ ПРОБЛЕМИ МЕТОДОЛОГІЇ СИСТЕМНОГО ІНЖИНИРІНГУ У ПРОЄКТУВАННІ ТРАНСПОРТНИХ СИСТЕМ

Анотація. *Представлено обрані проблеми методології системного інжинірингу у проєктуванні транспортних систем. Обговорювані методологічні проблеми сформовані на прикладі концептуального проєкту міської залізниці. Системний опис транспортного проекту наведено відповідно до принципів, що використовуються в системному інжинірингу. Описаний кейс стосується методології проектування концепції залізничної транспортної системи. У наведеному прикладі основною проблемою є розробка документу під назвою "Концепція міської залізничної системи (CoMRS) у міському районі Metropolis", який у Польщі подається як GZM. Передбачалося, що цей документ буде системним документом, розробленим з використанням методів системного інжинірингу з метою побудови, впровадження та розвитку сучасної комплексної системи залізничного транспорту, що охоплює міську територію GZM Metropolis. Тому, в першу чергу, було розроблено додатковий, але важливий документ "Методологію концепції системи міської залізниці (MoCoMRS)", який містить вичерпний методологічний опис того, як продовжити використання методів системного інжинірингу, необхідних для розробки CoMRS. Докладно наведено методичні вказівки щодо моделі V. При застосуванні системного інжинірингу у проєктуванні транспортних систем пропонується використовувати цю модель, яка організовує системну процедуру в процесі проєктування. Сформульовано рекомендації щодо використання цієї моделі та застосування методів системного інжинірингу для CoMRS, що стосуються, серед іншого, таких етапів проєктування: системні припущення, системні вимоги, проєктування високого рівня, детальний проєкт. Приклади концепції міської залізниці, представлені в цій статті, базуються на реальному транспортному проекті і поточною стадією є робота над попереднім техніко-економічним обґрунтуванням цієї залізничної системи. Це важливо, оскільки можна перевірити та ітераційно виправляти та оновлювати методологію проектування цієї системи залежно від мінливих умов і критеріїв, що є результатом, серед іншого, різних прагнень зацікавлених сторін, які формують вимоги до системи. Ця процедура також була включена в модель V на етапах розробки, будівництва та впровадження системи, а також на етапах інтеграції, перевірки та валідації елементів і всієї залізничної системи.*

Ключові слова: *транспортні системи, системний інжиніринг, модель V, міська залізниця, методологія, транспортний проєкт.*