

Framework for Proper Integration of Flexibility in Conceptual Designs of Energy and Industrial Infrastructures.

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Abstract

Flexibility is an important performance indicator of any engineered system, yet a term often vaguely defined in the infrastructure domain. We have identified that though infrastructures often have more complex external interactions than process systems; infrastructure flexibility could still be dealt with in the existing process systems engineering (PSE) framework if a proper conceptual definition of flexibility as well as appropriate flexibility taxonomy is developed. In this paper, a conceptual definition of flexibility which suits infrastructure design has been proposed. By means of the identification of the interactions between an infrastructure and its surroundings and of the systemic uncertainties, taxonomy for infrastructure flexibility is developed. Based on this definition and taxonomy, a systems engineering framework for the design of flexible infrastructures has been proposed. To test the application effectiveness and utility of the proposed framework, it has been qualitatively applied in the conceptual synthesis of an infrastructure (gas pipeline network) design problem.

Keywords: Flexibility, Performance Targets, Conceptual Design, Infrastructure.

1. Introduction

The definition of infrastructure is often heavily context-dependent; thus, it is worthwhile to give a working definition of infrastructure in the context of our paper. Infrastructure can be defined as a system of interdependent and interconnected networks of identifiable structures, facilities (physical installations), capital and functional pieces of equipment etc that provide a reliable production and distribution of products and services to society. This paper focuses on energy and industrial infrastructures.

Energy infrastructures can be functionally defined as those that satisfy the energy needs of the society. These include (Weijnen & Bosgra, 1999), infrastructures for:

1. petroleum and natural gas production, coal, ore extraction & mining
2. processing and conversion of resources to power and heat
3. end use conversion of gas, waste heat etc to district space heating etc
4. transportation and storage of oil, gas, coal, etc as well as those for the transportation and distribution of ready-to-use electricity gas and heat.

Industrial infrastructures: in the context of this paper, water, waste, and wastewater infrastructures have been classified as industrial infrastructures.

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Infrastructure and process systems share some conceptual or systemic similarities: large complex network systems that can be decomposed into a number of interconnected subsystems; both deals with the handling of various flows of material and information (Herder et. al, 2000) and with the transformation of these flows. Though both systems are complex networks, the degree and nature of complexity associated with them differs. At the structural level, the complexity of a process system seems larger (more components which are often inter-linked in different manners -mass, energy, control), but the interface with the outside world is simple (just a few streams entering and leaving). In contrast, the internal connectivity for an infrastructure is (on average) simpler, but the interactions with the system surroundings are far more diverse. With these differences in mind, infrastructures are in a sense, a logical and meaningful extension (to a higher level of aggregation), of process systems. These infrastructures, apart from their network and complexity characteristics, also must be designed in such a way that their functional survival in a fluctuating environment, full of uncertainties and changing requirements, is guaranteed to a significant degree. We posit that the optimum responsiveness of these infrastructures to these changing uncertainties & requirements can be realized through the intrinsic flexibility measures embedded in such infrastructures during the early phase of the conceptual design and re-design processes. This calls for a unified theoretical concept, explicit definition and a framework that give the designers, the opportunity to systematically integrate flexibility and reliability early on in the conceptual design phase of these highly networked energy and industrial infrastructures. In the PSE literature, flexibility has been given an exact mathematical treatment however, since infrastructures have more complex external interactions than process systems, the classical definition of flexibility from PSE only, may not be a priori sufficient to handle the infrastructure flexibility issues. Nonetheless, we conjecture that (given a precise definition), infrastructure flexibility could still be dealt with in an elaborated PSE conceptual framework, this, we set to test in this paper.

2. Conceptualization of infrastructure flexibility

The need for proper flexibility definition prior to their integration in infrastructure design can never be over-emphasised since flexibility is often misinterpreted because of ambiguity. In many disciplines, such as discrete manufacturing (aerospace & electronic systems) flexibility has been identified as a critical performance criterion but little has been done to unambiguously define it. Instinctively, flexibility is defined as the ability to respond to changes. This definition, though essential, falls short of differentiating it from other system properties such as robustness. We define flexibility as:

the property of a system, endowed by design, that gives the system the capability to respond to a specified range of changes and uncertainties, relative to the initial design requirements and objectives (functional, physical, economic and operational), in a timely and resource-effective manner satisfying the performance targets.

This is quite different from robustness, “the property of a system that allows it to satisfy a fixed set of requirements; despite changes occurring after the system has entered service, in the environment or within the system itself, from the nominal or expected system design parameters” (Saleh et al., 2003). Though there is a striking similarity in these two concepts (both refer to the ability of a system to handle change), the nature of

the change, as well as the expected system's reaction to the change, in each case differs (while flexibility follows the changes because of the dynamic nature of requirements it has to satisfy, robustness resists such changes because of the fixed nature of the requirement). Therefore, flexibility aims at satisfying changing requirements in a changing and often unforeseeable environment while robustness aims at satisfying a fixed set of requirements in also a dynamic and uncertain environment as depicted in figure 1. Robustness and flexibility should be complementary design features to deal with changes (to be followed or resisted) in the infrastructure environment. A robust and flexible system will cope with a range of changes without failure to fulfil its fixed and changing requirements. Since the features of energy and industrial infrastructures are such that the requirements on them are sometimes fixed and most of the times dynamic, in a dynamically uncertain environment, both robustness and flexibility capabilities should be embedded into their design.

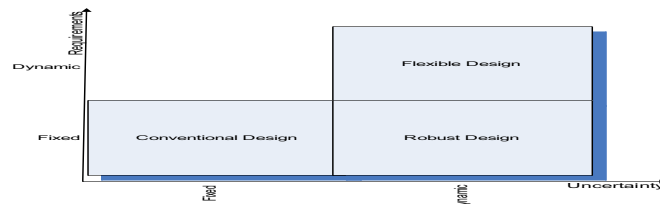


Figure 1. Relationship between robust and flexible designs.

2.1 Infrastructure Flexibility Classification

In classifying infrastructure flexibility, an understanding of the pattern of interaction between the designed system and its surrounding (through the system boundary) is necessary. It is our conviction that the manner of description of a system influences the identification of the possible changes that may take place and the interpretation of their demands for flexibility. This interaction is schematically shown in figure 2. From these interactions we have identified three distinct changes to which a flexible infrastructure design should respond to and have classified the different forms of infrastructure flexibility addressing these changes in line with Brown et al., (1984). These three distinct changes are: 1) external or “supply chain-driven” changes (which is associated with the material and information demand and supply to and out of the system). The forms of flexibility associated with this type of changes are the input related flexibility-raw material, utilities etc and the output related flexibility such as product flexibility, volume flexibility, expansion flexibility, mix flexibility. 2) Internal or process-driven changes, which take into account the entire internal changes at the system level (and have these subsets of flexibility classified under it: equipment flexibility, structural flexibility, and operational flexibility). 3) Institutional changes (this may sometimes have only an indirect effect on the design); nonetheless, to account for this form of changes, institutional uncertainties should be given consideration early at the design stage. In the PSE domain, greater emphasis is placed on the flexibility to respond to the process-driven changes. Since infrastructures do have more diverse interaction with the external world, a supplementary consideration of the “supply-chain driven” and institutional changes, and the flexibility types that could respond to them is necessary. We also view flexibility as a response (with a greater freedom of act in the design stage) to uncertainty. Hence, an upfront consideration of such uncertainties in a design is a pro-

active way of dealing with the flexibility issues of the design. The identification and mapping of such uncertainties into the right flexibility type early in the design process is therefore of paramount importance for the realization of a flexible infrastructure design.

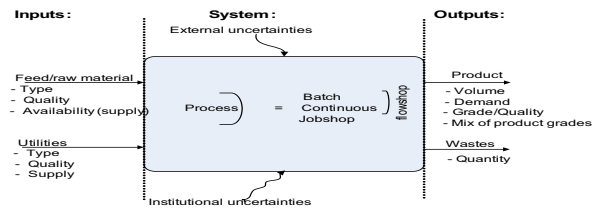


Figure 2. System interaction concept

In table 1, we have identified and classified the uncertainty types (sources) as well as the uncertain parameters and variables that are usually prevalent in the design process of infrastructure systems. Having identified the flexibility types, the changes necessitating them and their requirements, a framework for integrating such flexibility is required.

Table 1: Uncertainty classification

UNCERTAINTY TYPES (SOURCES)	UNCERTAIN VARIABLES
INPUT RELATED	
Raw material	Quality and quantity variation, prices
Utilities	Quality and quantity variation, prices
Supply market	Raw material and utilities availabilities
PHYSICAL SYSTEM (PROCESS) RELATED	
Flux (=internal rate of change)	Temperature, Pressure, Concentration
Capacity (=internal storage)	Flow rates
Operational	Utilization, product demands, feedstock supply, equipment availability, expansion
EQUIPMENT RELATED	
Costs	Purchase and operating costs
RAM	Reliability, availability and maintainability attributes
OUTPUT RELATED	
Products	Product specification, prices, demands
Demand market	Demands of products and by-products
INSTITUTIONAL RELATED	
Regulatory	Environmental emission index and other regulatory policies
Politico-economic	Liberalization, privatisation

3. Framework for integrating flexibility in infra-system designs

A framework aimed at providing effective decision support for integrating flexibility as well as reliability at the early stage of the conceptual designs of infrastructure systems is being proposed as shown in figure 3. Four spaces- requirement space, modelling space, design space and performance space have been identified in the framework as critical for the proper integration of flexibility. At the requirement space, the constraints and uncertainties of the design have to be identified, targets or range of flexibility with its associated robustness and adaptability parameters are set for the chosen design variables. In the modelling space flexibility/reliability/process model is developed, that satisfy certain functional requirements. At the design space the range or set of targeted design and control variables is synthesised, analysed, and adjusted to achieve optimal flexibility results. At the performance space, how well the system meets the technical, social and economic requirements set out in the requirement space are measured.

4. Illustrative test case

To test the application effectiveness and the ideas behind the framework, it has been applied to the conceptual design of a gas pipeline (transmission) network. The gas pipeline network to be designed is a typical energy infrastructure, which transports natural gas from a supply point (source) to several demand points (physical sinks) through the arcs (pipes and compressor stations). The ideas behind the framework are exemplified in a step-wise manner below; assuming a basis of design has been given.

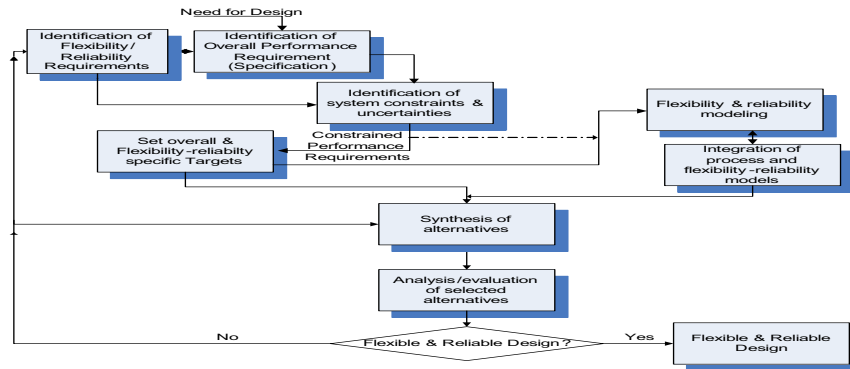


Figure 3. A framework for the integration of Flexibility in infrastructure design

Step 1: Identifying the overall system performance requirements: At this level the design performance requirements (quality factors), with special focus on flexibility is identified. In this test case, a multi-objective performance requirement (cost effective, reliable and flexible gas transmission pipeline network) is being identified.

Step 2: Identifying all the system variables, constraints and uncertainties : The principal variables for the pipeline network are identified as follows: pipe diameter, inlet pressure, limits of pipe stress; Throughput; Compressor station spacing; Delivery pressure limits; Line length; gas temperature and the spatial connectivity structure of the network. The design constraints include: nonlinear pressure drop constraints, pipeline material selection, availability of right of way and other physical restrictions etc. The uncertainties include: internal or system related uncertainties such as variations in the inlet and delivery pressures, costs, demand and supply (flow rates) of gas; failure rates and costs of components such as compressors, pipes, pumps; and external related uncertainties such as varying demand by customers, seasonal demands, gas sources that are temporarily out of order, compressor stations fuel gas consumption.

Step 3: Setting an overall target as well as flexibility & reliability targets: Here, preliminary attempt is made at establishing the flexibility requirements to handle the conceived uncertainties. Also, some scenarios and targets that will be used in the subsequent steps of the framework are set. For example setting a target range for the pipeline, compressor capacities. From the uncertainties identified above, it becomes apparent that both internal and external flexibilities will be needed to handle them. In the internal front, equipment, structural (how the network is to be connected), operational flexibilities is needed. External front - volume, expansion, input flexibility.

Step 4: Setting up a physical flexibility-reliability model as well as process models: The process model which relates the design variables (diameter, length of the pipes, capacity of the compressor) to other parameters is set up. For this case study such process model is well established (Thomaidis & Pistikopoulos, 1994). With the internal system flow-sheet and the associated system components, a flexibility model is developed, that satisfy certain functional requirements, the least of which is linking the design parameters of the system with a (computable) flexibility-reliability performance function. A stochastic scenario approach (to account for the uncertainties) can be taken. The uncertainties identified above are characterized by a probability distribution and

possible scenarios generated. Also, reliability models are needed, which define the states (operability) of the equipment and the rate of transition between the states.

Step 5: Integrating the process and flexibility-reliability (FR) models: Flexibility-reliability models & process models originally developed in parallel are now integrated.

Step 6: Synthesis of design alternatives: Targets set up-front is used within the integrated FR & process models for synthesis of design alternatives.

Step 7: Analysis, evaluation & optimization of the synthesised alternative(s): Based on the synthesised alternative(s), optimisation methods may be used to select design variable ranges or values that produce optimal flexibility reliability performance. The optimization may be carried out within a multi-objective stochastic framework such as:

$$\begin{aligned} & \text{Max} \quad E(f_1, f_2, f_3) \\ & \text{s.t} \\ & h^\omega(x, y, d, z, \theta) = 0, \omega \in \Omega \\ & g^\omega(x, y, d, z, \theta) \leq 0, \omega \in \Omega \end{aligned}$$

Where $E(f_1, f_2, f_3)$ is an expected joint flexibility-reliability-economics multi-objective function of the system, computed over all scenarios Ω , $h^\omega(\dots)$ and $g^\omega(\dots)$ are vectors of scenario-indexed equality and inequality constraints, respectively. ω is the set of generated scenarios, and θ represents the uncertainties; d, x, z, y are the vectors of design, state, control and binary variables respectively. A “pareto” form of solution is sought where an intrinsic trade-off between economics and the desired flexibility-reliability is made. Iteration may be made if evaluation results look unsatisfactory.

5. Conclusion and Future work

Infrastructures are in a sense; a logical and meaningful extension of process systems, thus, given a proper definition of infrastructure flexibility, the classical PSE flexibility concept seems well applicable to classes of infrastructures. Consequently, a conceptual definition and taxonomy of infrastructure flexibility based on their interactions with the surroundings has been suggested. A framework is proposed for integrating such needed flexibility and reliability early in the designs of networked infrastructures. The application of the framework was conceptually illustrated by means of a gas pipeline network design. However, the framework effectiveness needs to be further developed by the derivation of a quantitative flexibility performance measure, the practicality of which is to be tested by means of quantitative case studies.

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