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A METHODOLOGICAL FRAMEWORK FOR THE EFFECTIVE DEPLOYMENT AND THE OPERATIONAL OPTIMIZATION OF FLEXIBLY AUTOMATED PRODUCTION AND SERVICE SYSTEMS

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ABSTRACT

The ongoing efforts for ever increasing automation of the contemporary production and service systems are usually challenged by the lack of a well-developed formal theory for managing the representational and computational complexities that result from the large-scale nature and the operational complexity of the corresponding applications. Currently, these complexities are addressed by further structural and behavioral restrictions imposed at the design level, which simplify the design process but also render the final system quite rigid, and therefore, inflexible and inefficient. The presented research program seeks to address these limitations by (i) abstracting the considered systems to a class of resource allocation systems (RAS), and (ii) developing effective and efficient control policies for these RAS through the employment of qualitative and quantitative Discrete Event System (DES) theory. The derived results are applied to the scheduling of capacitated re-entrant lines, i.e., re-entrant production lines with finite buffers at their workstations.

1 CONTEXT AND MOTIVATION OF THE PRESENTED RESEARCH

The quest for an ever increasing level of automation is a prevailing trend in many sectors of the modern economy, ranging from the contemporary production systems and their supporting material handling systems, to the various "intelligent" transportation systems that are currently employed or contemplated for the future transport needs, to the internet-based workflow management systems that have been proposed for the mechanization of various routine operations taking place in service sectors like banking, insurance claiming, and the backend transactions of contemporary logistics systems. However, the existing theory for supporting the deployment and the real-time management of such automated operations is challenged by the operational complexity and the large-scale nature of the corresponding applications. In this presentation, we shall outline an ongoing research program that seeks to develop a novel methodological framework for supporting the effective deployment and the real-time management of the operations that take place in the aforementioned contexts. The successful completion of the considered program will enable a streamlined and a more robust deployment of the automated operational modes that are sought for these applications, and it will help materialize the operational flexibility and efficiency that have been contemplated for them.

2 OUTLINE OF THE PRESENTED RESEARCH PROGRAM AND ITS METHODOLOGICAL BASE

From a methodological standpoint, the considered research program abstracts the aforementioned operations as a class of resource allocation systems (RAS) that must be controlled for (i) the typical time-based performance indices that are sought from the considered environments, like the maximization of their throughput and the minimization of the latencies experienced by the underlying processes, but also for (ii) the operational safety, behavioral correctness and logical consistency that are necessary for guaranteeing the effective autonomous operation of the underlying applications. To this end, the presented research program seeks to leverage the existing theory of RAS supervisory control for liveness and deadlock-freedom, developed by the first author and his collaborators, and complement this theory with the necessary performance-oriented control / scheduling theory that will lead to the complete development of a real-time control framework for the considered RAS. The resulting scheduling problems bear significant similarity to the scheduling problems that arise in the context of the complex stochastic networks that have been recently addressed by modern queueing theory. But the presumed finiteness of the underlying system structure and resources – a critical attribute for developing solutions that are effective and robust in the context of the pursued automation – gives rise to blocking and deadlocking effects that negate some of the most classical and most powerful results of that theory. On the other hand, the same set of traits of the underlying systems implies that their dynamics evolve over finite state spaces. Hence, under a standard approximation of the involved (inter-)event times by phase-type distributions, the resulting scheduling problems can be formulated, in principle, as Markov Decision Processes (MDPs). Furthermore, thanks to the employment of the aforementioned results on RAS liveness-enforcing supervision and deadlock avoidance, these MDPs present additional structure with respect to (w.r.t.) the underlying state space and the subspaces admitted by the various candidate policies, that renders them amenable to some of the most powerful analytical and computational results of MDP theory. However, a remaining substantial challenge is the curse of dimensionality that is defined by the explosive sizes of the underlying state spaces, even for RAS structures of fairly small size. In fact, the humongous sizes of these state spaces render intractable even the representation / statement of an optimal policy for the considered scheduling problems (since such a representation must specify an optimal action for every state of the underlying state space).

Faced with these representational and computational challenges, the presented research program seeks to confine the aforementioned scheduling problems to policy spaces that admit more tractable representation and computation w.r.t. the underlying state spaces, and are practically relevant. Instrumental to this task is the employment of some formal modeling frameworks of Discrete Event Systems (DES) theory that provide a parsimonious and unambiguous representation to the underlying RAS structure and the adopted operational policies, and facilitate a rigorous analysis of the impact of these structural and behavioral traits upon the system performance. In more concrete terms, these representations enable a succinct definition and parameterization of the target policy spaces, and the effective optimization over these parameter spaces using results from the theory of Markov reward processes and simulation-based optimization. Finally, the scheduling policies that are derived along the aforementioned lines can be perceived as the result of certain aggregations imposed on the underlying state spaces, and the presented framework also offers the possibility of the refinement of these policies for further performance enhancement through controlled disaggregation.

3 CONCLUDING REMARKS

Closing this brief discussion of the considered research program, we want to make the following additional remarks: As already mentioned, the scheduling problems addressed by the presented program fall in the broader area of scheduling of queueing / stochastic networks with blocking, a class of networks with very limited results when it comes to their scheduling. The expected effectiveness of the proposed program stems from its ability to decompose these problems into the logical / behavioral and the performance control / scheduling sub-problems discussed above, and this decomposition is attained by leveraging results from qualitative and quantitative DES theory. This theory provides succinct representational frameworks and powerful analytical tools that enable the rigorous analysis of the addressed problems, and the systematic management of the involved complexities. Hence, the derived results will extend the boundary of the existing scheduling theory, while, at the same time, they can also support the development of practical computational tools for the considered applications. Finally, the presented program promotes DES theory itself, by taking advantage of the special structure that appears in the two sub-problems mentioned above, and also by being among the very few initiatives that are developing at the interface of qualitative and quantitative DES theory.