

## 審 査 の 結 果 の 要 旨

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高 思霄 proposed the thesis that is named by「Efficient Buffer Design of Production Lines Based on Modular Queues (モジュラーキューに基づく効率的な生産システムのバッファ設計)」. In the thesis, there are seven chapters.

Production lines, which are widely used in industry, comprise materials, work areas and storage areas. Materials enter a production line and flow among work areas and storage areas until they depart from it. In the language of queueing theory, discrete parts in the materials transferred in the production line are called jobs. The work areas that provide production operations are called servers. The storage areas that maintain enough supplies to keep production operations running smoothly are called buffers. Buffers are very important for the design, optimization and management of production lines. Excessive buffers increase system redundancy and waste cost, while insufficient buffers lead to congestion and low profits. Therefore, buffers should be designed properly. Agile manufacturing is to respond quickly to customer and market needs. Agile design that serves for the agile manufacturing requires a rapid buffer design process to estimate the potential success and values of a production line design plan. Therefore, it is necessary to propose an efficient buffer design methodology that designs buffers for production lines rapidly with acceptable solution quality. The thesis solved the rapid buffer design problem from two aspects: one is to propose a layout approach of buffer topology network to obtain a buffer topology network of a production line with proper designed buffers required to meet some specific objectives. The buffer topology network refers to a designed production line topology just involving servers, buffers, and location relationships among them. The thesis classifies commonly used buffer topology networks of a production line into proper groups to decrease candidate buffer topology networks for the proposed layout approach. By this method, computation time of the buffer topology network layout can be decreased; the other one is to propose an efficient buffer allocation approach to rapidly allocate proper buffer size into a production line to satisfy some specific objectives. In the thesis, the proposed bottleneck

indicator is used to search the real bottleneck of a production line rapidly and one buffer is increased before the bottleneck to increase buffer effectively. The variable neighborhood search algorithm is used in the case of not obtaining the real bottleneck of the production line to keep acceptable solution quality. Moreover, to evaluate the effectiveness of the buffer design solution, a performance evaluation methodology that is an efficient throughput analysis methodology is developed firstly. The proposed throughput analysis is developed based on modular queues and can calculate the throughput of a production line rapidly with acceptable solution quality.

In the thesis, three approaches were proposed to achieve the efficient buffer design of production lines including the efficient throughput analysis approach, the efficient buffer allocation approach and the layout approach of buffer topology networks.

Throughput analysis is used to evaluate buffer design solutions in the thesis. The throughput is rate at which jobs finish a production process and leave the production line (i.e., the average number of jobs leaving the production line per second). The throughput of a production line with infinite buffers was usually analyzed before. However, the solution obtained by these methods may be not applicable to real production lines where both the number of buffers and the capacity of a buffer are finite. To make modeling and solution methods more applicable to practical application, finite buffers should be considered in the modelling and throughput analysis of production lines in the thesis. In this study, an efficient throughput analysis approach based on queue modules is presented for production lines with serial, merging, splitting, and recirculating topologies. The queue modules are proposed based on not only decomposition methods but also standardized and automation calculation ideas. The queue modules are decomposition models with standardized structure. Based on the queue module, the decomposition regulation is defined to decompose a production line models with serial, merging, splitting and recirculating topology into several queue module. By using the queue modules and the decomposition regulation, decomposition process of the production line models can be accelerated, and computation time is decreased. By iteratively calculating state probabilities of the queue modules, the throughput of production lines can be obtained. To decrease the computation time and automate the calculation process of the queue module state probabilities, a queue module database that includes the solution equations of common queue module state probabilities is built in advance. Moreover, an iterative approximation method is improved for calculating and iterating the queue module state probabilities in production line with serial, merging, splitting and recirculating topologies until the throughput is obtained. The proposed throughput analysis approach calculates the

throughput of production lines with serial, merging, splitting, and recirculating topologies rapidly (completed in 600 s) with acceptable solution quality ( $\geq 90\%$ ). The study not only meets the requirement of rapid evaluation of buffer design solutions involving buffer allocation solutions and layout solutions of buffer topology network, but also contribute to rapid throughput analysis that is more applicable to practical application in industry.

Buffer allocation study is a very challenging problem in the design, optimization and management of production lines. To serves agile design, buffers should be allocated into production lines rapidly, meanwhile acceptable solution quality is also required. In the study, an efficient buffer allocation approach is proposed to determine suitable locations for buffer allocation to satisfy the desired throughput while achieving a good balance between solution quality and computation time. The proposed buffer allocation approach can be divided into two parts: one is an evaluative method that is the proposed efficient throughput analysis approach; the other one is a generative method that generate candidate buffer allocation solutions. The extended active probability-based variable neighborhood search algorithm is proposed as the generative method to detect suitable locations for buffer allocation and increase buffers. In the algorithm, the extended active probability that is a bottleneck indicator is used to rapidly detect the real bottleneck from several candidate bottlenecks of a production line and increase buffers. This indicator proves to be highly effective for production lines with serial, merging, splitting, and recirculating topologies. The variable neighborhood search algorithm is used to avoid local optimal solutions and maintain acceptable solution quality. In the case of not obtaining the real bottleneck in the initial neighborhood structure, the additional neighborhood structure is used, and more candidate bottlenecks are detected to search the real bottleneck. The proposed buffer allocation approach can rapidly allocate buffers into production lines with serial, merging, splitting and recirculating topologies. Even for a production line with large-scale topology, computation time of the buffer allocation is less than 28800 s. In addition, the proposed efficient buffer approach can achieve better solution quality within a short computation time compared to former methods and maintain solution quality close to extend tabu search algorithm within a long computation time. The extend tabu search algorithm has been proved to have high solution quality. This meets the requirement of acceptable solution quality. The proposed buffer allocation approach can facilitate agile design of production lines in industry by rapidly estimating the topology and cost of a production line.

The Buffer topology network layout is also very important in the buffer design. The study is to obtain a buffer topology network of a production line that can achieve the

desired throughput with proper designed buffer size. Compared to the buffer allocation problem, the layout problem of buffer topology network is more difficult, because not only buffer size and server size, but also their location relationships are designed. Moreover, there are so many kinds of buffer topology networks that it is impossible to test all of them to design a proper buffer topology network. To solve the difficult problem, it is a good choice to start studying from commonly used buffer topology networks and select proper candidate buffer topology networks. In the study, the layout approach of buffer topology network based on MECE principle is proposed to obtain a buffer topology network of a production line that satisfies the desired throughput. A proper classification of candidate buffer topology networks can decrease the number of candidate buffer topology networks and reduce computation time of the buffer topology network layout. By the classification method based on MECE principle, commonly used buffer topology networks are classified into four groups according to different server arrangements and buffer topologies. The server arrangements consider two types including server serial arrangements and server parallel arrangements. The buffer topologies consider two types including acyclic buffer topologies and recirculating buffer topologies. By combining the two types of server arrangements and two types of buffer topologies, four buffer topology networks that represent four groups including a server serial-acyclic topology, a server serial-recirculating topology, a server parallel-acyclic topology and a server parallel-recirculating topology are used as candidate buffer topology networks in the proposed layout approach of buffer topology networks. By the proposed buffer allocation approach, buffers are allocated into the four candidate buffer topology networks and their corresponding throughput are calculated by the proposed throughput analysis approach, respectively. The result of the buffer topology network layout is the best buffer topology network topology with the fewest designed buffers required to achieve the desired throughput. The contribution of the study is to propose the layout approach of buffer topology networks based on the classification of buffer topology networks. Moreover, the study also verifies the feasibility of the buffer topology network layout based on the classification of buffer topology networks, which selects proper candidate buffer topology networks and decreases the computation time of the buffer topology networks layout apparently.

In summary, the study in the thesis can be applied to rapid buffer design of production lines. The proposed efficient throughput analysis approach can obtain the throughput of production lines with serial, merging, splitting and recirculating topologies in 600 s. The relative errors between the throughputs obtain by the proposed throughput analysis approach and simulation data obtained by a commercial simulator

are lower than 10%. The proposed efficient buffer allocation approach can achieve rapid buffer allocation to satisfy the desired throughput. The buffer allocation process can be finished in 28800 s with acceptable solution quality even for a complex production line with 50 servers and buffers. Compared to former methods, the proposed buffer allocation approach can keep higher solution quality within a short computation time.

Finally, from various perspective, the application and limitation of the proposed approaches in the thesis were discussed: for the efficient throughput analysis approach, it is developed based on queue modules that are the key to automate the decomposition and calculation process of production lines. The queue modules represent the idea of standardized decomposition and automate calculation, which is very useful to decrease computation time of the throughput analysis. The proposed throughput analysis can be used to rapidly calculate the throughput of production lines in industry, however, more decision variables such as blocking type should be improved to make the proposed efficient throughput analysis approach be more applicable to more kinds of production lines in industry; for the efficient buffer allocation approach, it achieves a good balance between solution quality and computation time to solve the buffer allocation problem, and serves agile design in industry by rapidly detect suitable buffer update locations and increasing buffers. However, to decrease the computation time of the buffer allocation further, one improvement is to increase several buffers in each buffer update. For the proposed layout approach of buffer topology networks, the number of candidate buffer topology networks is decreased apparently in the layout problem of buffer topology networks by classification of buffer topology networks. However, both the number and location of recirculating structures should be considered in the classification of buffer topology networks to analyze the effects of the recirculating structures on the topology network throughputs.

The thesis studied a very difficult but meaningful and practical problem in industry. In the thesis, to realize practical application, appropriate assumptions, modeling and research objectives were selected. The proposed methodologies have been verified in numerical examples in which the proposed methodologies were compared to former studies. The results of the numerical examples show that the proposed methodologies can solve the practical problem and be practically used in industry.

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