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Collaborative Optimization of Planning and Control for Large Equipment Service-oriented Manufacturing Based on Lean Logistics

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Abstract: In order to overcome the problems in current literatures, that is neglect of collaborative effects and lean operation and the simple weighted method for dealing with the relations of quality, duration and cost, the collaborative optimization of planning and control for Large Equipment Service-oriented Manufacturing (LESM) is studied systematically based on lean logistics. Firstly, the necessity of collaborative optimization of planning and control were analyzed, as well as the lean logistics objective and the relationship among three objectives of quality, duration and cost. Secondly, introducing the Taguchi quality loss function and punishment factor, the coordination model of quality-duration-cost was established based on the cost. Thirdly, considering coordination among levels of project and quality-duration-cost, a multi-level and multi-objective coordination optimization model of planning and control was built. Fourthly, integration algorithm of simulation modeling and genetic algorithm (SM and GA) was designed and effectiveness was verified by case study. This provides a theoretical method for LESM planning and control.

Key words: Service-oriented manufacturing, planning and control, collaborative optimization, taguchi quality loss function, lean logistics

INTRODUCTION

At present, the large equipment manufacturing enterprises in China are transforming from pure product manufacturing to service-oriented manufacturing which can provide whole solutions for client and headed to the high-end of industrial value chain via value-added services. With large equipment manufacturing enterprises as the core, Large Equipment Service-Oriented Manufacturing (LESM) can provide a whole set of solutions considering product life cycle by integrating the social recourses. According to the demands of customers, the solutions include design (project, process and equipment), product manufacture, construction, installation and debugging and after-sales service.

Unlike traditional manufacturing, the LESM is characterized by complexity, distribution, dynamic and uncertainty, as well as multi-level and multi-objective for operation structure. The larger scale of operation planning control causes, the more difficulty solution stability we can control. So planning control problems should not only realize optimization but also collaborative effect of multi-level and multi-objective. This is a new problem and need of large equipment manufacturing enterprises in the transformation. And the research of collaborative

optimization model is considered as an acknowledged NP-hard question. As a result, it is a challenge to study due to the few relative research results and incomplete theory system so far.

It has been more than 50 years since Modigliani and Hohn (1955) started to study the operational planning control optimization under traditional mode. Despite the numerous research results, there is a huge difference between content of the results and the practical states as well as the requirements of industry (Kempf *et al.*, 2011). Along with the development of technologies, the planning control research will head to integrated, dynamically practical, multi-objective and highly optimized aspects and develop from centralized production to distributed production (Argoneto *et al.*, 2008). And the current planning control problems are the collaborative integrated decision issues from high level to low level (Maravelias and Sung, 2009). In the recent years under complicated environment, the planning control optimization research mainly include network distributed planning and scheduling (Shah and Ierapetritou, 2012; Al-e-Hashem *et al.*, 2011; Mohammadjafari *et al.*, 2011), planning and scheduling under supply chain (Zhang *et al.*, 2011a; Kim *et al.*, 2008; Voss and Woodruff, 2003; Li and Womer, 2012), scheduling research of

production project under uncertain situations (Luo and Rong, 2009; Zhang *et al.*, 2011b), multi-projective integrated progress optimization (Liang, 2012) and collaborative planning and scheduling optimization of multi-companies (Zhang *et al.*, 2012). In the research of project plan, it has tended to the multi-projective research in objective optimization (Dan *et al.*, 2011; Li *et al.*, 2008; Yin, 2011; Zhang *et al.*, 2009) and the method has been directed from applying PERT network (Wang *et al.*, 2012), critical chain (Liang, 2012; Chen *et al.*, 2009), network planning technology (Qiao *et al.*, 2011) and system dynamics (Wang and Li, 2010) to use intelligent optimization algorithm (Peng and Wang, 2010). In order to study the tradeoff optimization problem of resource-constrained duration, cost and quality, the multi-attribute utility theory has been applied and the comprehensive weighted balanced relation model of quality-cost, duration-cost and quality-duration has been established in the references (Dan *et al.*, 2011; Li *et al.*, 2008; Wang *et al.*, 2004).

Based on current research, there are still problems like the difference between current situation of relative planning control optimized research and practical state, neglect of collaborative effects and lean operation and the simple weighted method used for dealing with the relations of quality, duration and cost. This paper focused on the LESM planning control optimization problems. Combining with the typical companies, the lean logistics was integrated into operational planning and control process and Taguchi quality loss function and penalty factor were introduced to establish a quality-cost-duration collaborative model. Also, taking quality-cost-duration into account, a multilevel and multi-objective collaborative optimization model was constructed. And model algorithm was explored. In addition, they lay a theoretical foundation for large equipment enterprises to transform to service manufacturing.

ANALYSIS OF PLANNING AND CONTROL FOR LESM

Necessity of collaborative optimization of planning and control for LESM: The LESM planning and control belongs to a multi-level and multi-objective collaborative optimization problem. The main task is to build a collaborative optimization model and explore collaborative optimization algorithm. As a result, the multi-level collaborative optimization is to minimize the cost of subentry and the overall project. That is multi-objective collaborative optimization of quality, duration and cost. The relationship among quality, duration and cost is

opposed as well as unified mutually (Wang *et al.*, 2004). These three goals are interconnecting, interplaying and intercoupling. It is hard to get a satisfying outcome if only pursuing one controlling target. So it needs to collaboratively consider equilibrium optimization of quality, duration and cost.

Lean logistics objective of LESM planning and control: The lean logistics objective of planning control is to realize the continuity, coordination, equilibrium and economy. The continuity means just-in-time (JIT) operational method with closely joined links. No waiting and tardiness happens to make sure the due date. The coordination is that various resources involved in service should be unified commanded and work closely in unison, not shuffle, not wrangle. The equilibrium will control the load and progress and prevent crashing to ensure the safety and quality. And the economy means that the overall planning and scheduling of the sequencing, quantity and time of various resources and decreasing the waste to reduce the operational cost. Therefore, the lean logistics goal will be reflected in the quality-duration-cost of overall project and subproject.

RELATION MODEL OF QUALITY, DURATION AND COST

The relation models about quality-duration-cost among quality-cost, duration-cost and quality-duration were used to be established by applying the theory of multi-attribute utility function (Dan *et al.*, 2011) and be weighted comprehensively. However, we thought the relation among quality, duration and cost cannot be simply weighted. Quality and duration for a project are both related to cost and they also have dialectical relation themselves. The three objectives of quality, duration and cost can be converted to cost single objective to optimize, through applying the relationship model of quality-duration-cost, in which quality and duration targets are both converted to the cost target. It is more operable and practical. In this paper, Taguchi quality loss function was adopted to build quality-duration-cost relation model.

Relation model of quality and cost: The quality cost mode is built depend on quality loss function. If the normal target cost for term i is C_i^0 , the quality loss is C_i^{Lq} , the quality target value is Q_i^0 , the quality loss coefficient K_q , the real quality is Q_i and the penalty for quality issues is F_i^q , then the quality loss is:

$$C_{ij}^{Lq} = k_q (Q_{ij} - Q_{ij}^0)^2 + F_{ij}^q \quad (1)$$

Relation model of duration and cost: The relation between cost and duration is similar with quality and cost. So the duration loss function can be reached by quality loss function. Assuming that the loss for term i caused by duration change is C_i^{Lt} , the target value is T_i^0 , the coefficient is K_i , and the real duration is T_i . The penalty for tardiness is F_i^t , so the duration loss function is:

$$C_{ij}^{Lt} = k_t(T_{ij} - T_{ij}^0) + F_{ij}^t \quad (2)$$

Relation model of quality-duration-cost of multi-level: For LESM project which has ij sub-projects, the quality loss for ij th term is: $C_{ij}^{Lq} = k_q(Q_{ij} - Q_{ij}^0) + F_{ij}^q$ and the duration loss for ij th term is: $C_{ij}^{Lt} = k_t(T_{ij} - T_{ij}^0) + F_{ij}^t$. Considering the quality loss and duration loss, the real cost for ij th term C_{ij} is equal to the sum of the normal target cost C_{ij}^0 , quality loss C_{ij}^{Lq} and duration cost C_{ij}^{Lt} . Then the coordination model of quality-cost-duration is expressed by the equation as followed:

$$C_{ij} = C_{ij}^0 + C_{ij}^{Lq} + C_{ij}^{Lt} = C_{ij}^0 + k_q(Q_{ij} - Q_{ij}^0)^2 + F_{ij}^q + k_t(T_{ij} - T_{ij}^0)^2 + F_{ij}^t \quad (3)$$

Therefore, the total real cost C for the entire project equals to the sum of the real cost for all sub-project:

$$C = \sum_{i=1}^n \sum_{j=1}^m C_{ij} = \sum_{i=1}^n \sum_{j=1}^m (C_{ij}^0 + C_{ij}^{Lq} + C_{ij}^{Lt}) = \sum_{i=1}^n \sum_{j=1}^m [C_{ij}^0 + k_q(Q_{ij} - Q_{ij}^0)^2 + k_t(T_{ij} - T_{ij}^0)^2 + F_{ij}^q + F_{ij}^t] \quad (4)$$

Consequently, it turns the quality, duration and cost problems into cost problems and multi-objective into single objective. It can also evaluate the project and resources' performance efficiently.

MULTI-LEVEL AND MULTI-OBJECTIVE COLLABORATIVE OPTIMIZATION MODEL

Basic hypothesis: (1) Only to study the collaborative planning control between companies that offer services and resources and not to involve the internal operation process of each company. (2) No interruption of service task during execution and the start time of every subtask is restricted by sequence. (3) Every subtask is only implemented by one federated resources but each

resource can undertake multiple manufacture and service task at the same time. (4) The operation mode is JIT, ignoring the inventory cost.

Parameter setup: Assuming in the contract of certain LESM project, the total price is p . The required quality is Q^0 and the due date is D . There are k federated resources involved ($FR = \{k, k = 1, 2, \dots, K\}$). Thus LESM project is $I = \{I = 1, 2, n\}$, subentry is $J = \{j = 1, 2, \dots, m\}$ and the lower item is $P = \{ijp, I = 1, 2, \dots, n, j = 1, 2, \dots, q\}$. For P th item in the j th subentry of the i th project, the service price P_{ijp} , number N_{ijp} , quality Q_{ijp} , due date t_{ijp} , the expected value of due date τ_{ijp} , start time ts_{ijp} and finish time te_{ijp} are expressed clearly. And ζ is the random factor of allowance.

Establishment of collaborative optimization model: Through establishing the quality-duration-cost collaborative model and considering multi-level collaboration, the non-linear multi-level and multi-objective collaborative optimization model for LESM planning control is built.

The whole project's quality-duration-cost collaborative optimization mode:

$$Z(C) = \text{Min} \sum_{i=1}^n \sum_{j=1}^m [C_{ij}^0 + k_q(Q_{ij} - Q_{ij}^0)^2 + k_t(T_{ij} - T_{ij}^0)^2 + F_{ij}^q + F_{ij}^t] \quad (5)$$

$$\max_{i \in n} \max_{j \in m} \max_{p \in q} te_{ijp} - \min_{i \in n} \min_{j \in m} \min_{p \in q} ts_{ijp} \leq D \quad (6)$$

$$ts_{ijr} + M(1 - y_{ijrp}) \geq te_{ijp}, i \in n, r, p \in q \quad (7)$$

$$te_{ijp} - ts_{ijp} + \zeta \leq \tau_{ijp}, i \in n, j \in m, p \in q \quad (8)$$

M is any positive number:

$$y_{ijrp} = \begin{cases} 1, & \text{if } p \text{ finishes earlier than } r \\ 0, & \text{otherwise} \end{cases}$$

Equation (6) is the duration target of the total project and it requires that the time difference between the earliest starting sub-project and the latest finishing sub-project should not expire the period of the whole project. Equation (7) is the constraint of time sequence among each subentry and Eq. 8 is the constraint for duration of subtask. Also the finish time te_{ijp} minus start time ts_{ijp} and plus time allowance ζ should not larger than the duration τ_{ijp} . In addition, y_{ijrp} is a decision variable.

ALGORITHM DESIGN OF SIMULATION AND GENETIC

The method of simulation modeling and genetic algorithm is integrated to solve this dynamic, non-linear and multi-objective optimization mode and to get the optimal solution:

- Step 1: Simulation modeling (SM):** The object-oriented simulation software Plant Simulation is used to build the simulation model and set the parameters of certain large equipment complete service
- Step2: Genetic algorithm (GA):** (1) Coding: Such as project item is ij , the chromosome gene code is n ($n = 1, 2, \dots, i \times j$) and the length is iHj for ij th subentry. The code for federated resources FR_k is k and its string type. The result of decoding is the matrix $[ij, FR_k, T_{ijst}, t_{ijre}]$; (2) Fitness evaluation: from Eq. 5, $fitness(x) = \min Z(C)$; 9; (3) Genetic manipulation: including generation number, generation level, population size M , crossover rate pc , mutation rate pm and termination code and so on; (4) Terminal condition: the

termination method is to decide a biggest genetic generation number T and the iteration will end automatically when it reaches the pre-set biggest reproductive generation number

CASE STUDY FOR LESM

Sample data and basic requirement: There is a LESM project which is a complete service of design, manufacture, construction and installation and debugging for a new dry process clinker product line with daily output of 4500 tons of cements and its preheating power generation equipment. The total value of the contract is 186 million Yuan (¥) and the total duration required is 420 days. There are 7 main federated resources or partners (not including some suppliers and outsourcing) through tendering and bidding. The decomposition and basic data of project are shown in Table 1. According to the contract, the penalty for delaying is 10,000 Yuan day⁻¹. The unqualified products must be reworked to guarantee the quality at their own cost, otherwise, the unqualified products cannot get paid. The ability of logistics transportation can be guaranteed and it will follow the conductor in time. So it will not affect the duration and

Table 1: Basic data for LESM project

Subitem i (9)	Subentry (j)	Price (Wan yuan) Pij (18600)	Duration Tij (66)	Pre-task Cijk	Target cost (Wan yuan) K	Source code
Engineering design	Preliminary design	50	8		40.0	1
	Process design	400	58	10	102.4	2
	Civil engineering design	250	44	10	131.2	3
	Public design	260	50	10	81.2	4
Main equipment manufacturing	Cement Equipment	6695	93	10	5802.2	5
	Power generation	3720	103	10	3422.4	6
Auxiliary Equipment procurement	Auxiliary cement equipment	445	60	10	386.5	10
	Auxiliary power generation	670	60	10	579.7	20
Civil engineering construction	Plant building	2200	100	12	1902.4	30
	Foundation of equipment	880	92	11, 41	731.2	40
Installation and trial run	Cement equipment	2100	100	11, 21, 4, 3	1802.4	50
	Power generation	780	100	11, 22, 4, 3	631.2	60
Road network greening		90	92	13, 4	150.0	70
System connection		0	8	5	0.0	0
Linkage test		0	22	6, 7	0.0	0

Table 2: Parameter setup for LESM modeling

Project name	Project code	Duration (days)	Target cost (wan yuan)	Project start symbol	Project rework symbol	Project ends symbol
Preliminary design	10	8	40.0	sp10	spfl0	spe10
Process design	11	58	102.4	sp11	spfl1	spe11
Civil engineering design	12	44	131.2	sp12	spfl2	spe12
Public design	13	50	81.2	sp13	spfl3	spe13
Cement equipment manufacturing	21	93	5802.2	sp21	spfl21	spe21
Power equipment manufacturing	22	103	3422.4	sp22	spfl22	spe22
Purchasing cement auxiliary	31	60	386.5	sp31	spfl31	spe31
Purchasing power auxiliary	32	60	579.7	sp32	spfl32	spe32
Plant building	41	100	1902.4	sp41	spfl41	spe41
Foundation construction	42	92	731.2	sp42	spfl42	spe42
Cement equipment installation and trial run	51	100	1802.4	sp51	spfl51	spe51
power generation installation and trial run	52	100	631.2	sp52	spfl52	spe52
Road network greening	6	92	150.0	sp6	spfl6	spe6
System connection	7	8	0.0	sp7	spfl7	spe7
Linkage test	8	22	0.0	sp8	spfl8	spe8

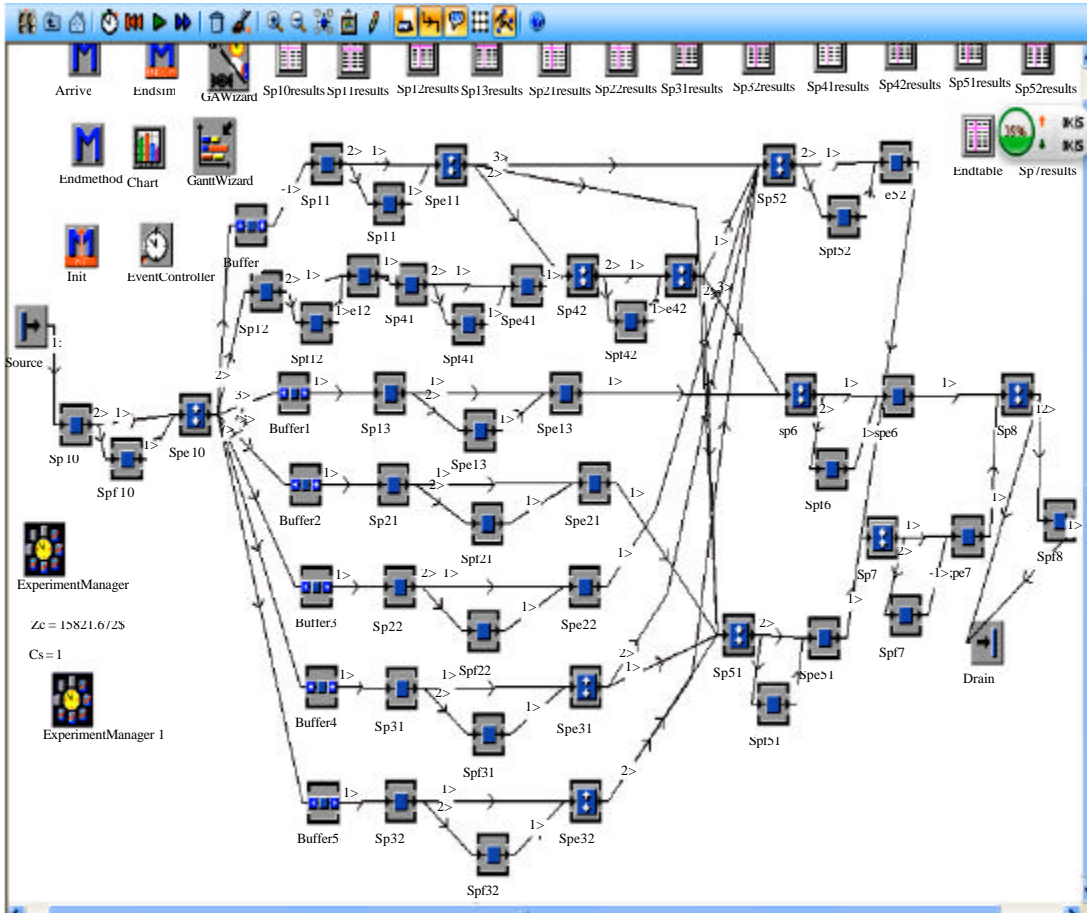


Fig. 1: Plant simulation model

quality, which will be ignored in this paper. The requirement is to solve the optimal project plan and to evaluate the control, $\zeta = 0.10$.

Establishment of simulation model based on genetic algorithm: (1) *Parameters setup:* The quality is qualified to 1 while unqualified to 0. Quality loss coefficient is ρ times as much as target cost. The parameters like ratio is $\rho = 0.1$ of reworking fee to objective cost. These are planned to calculate the Method program of the objective function value C , quality loss function value LQ and duration loss function value LT . Other parameters are shown in Table 2. (2) Establishment of simulation model based on Em-Plant: According to the simulation model is built by Plant Simulation, as shown in Fig.1. The finish time for each subtask must meet the requirement of the lean operation which is delivery on time, no advance and avoiding the waste. (3) Genetic algorithm setup: The number of genetic race is 20 and the population size is

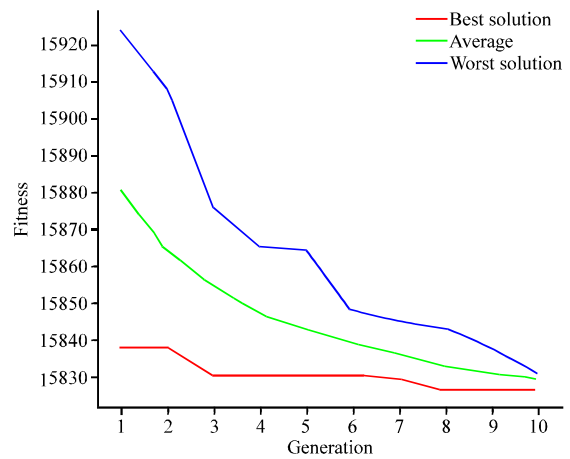


Fig. 2: Convergence value of fitness

100 with the crossover probability of 0.9 and mutation probability of 0.15. The start time of subtask is the

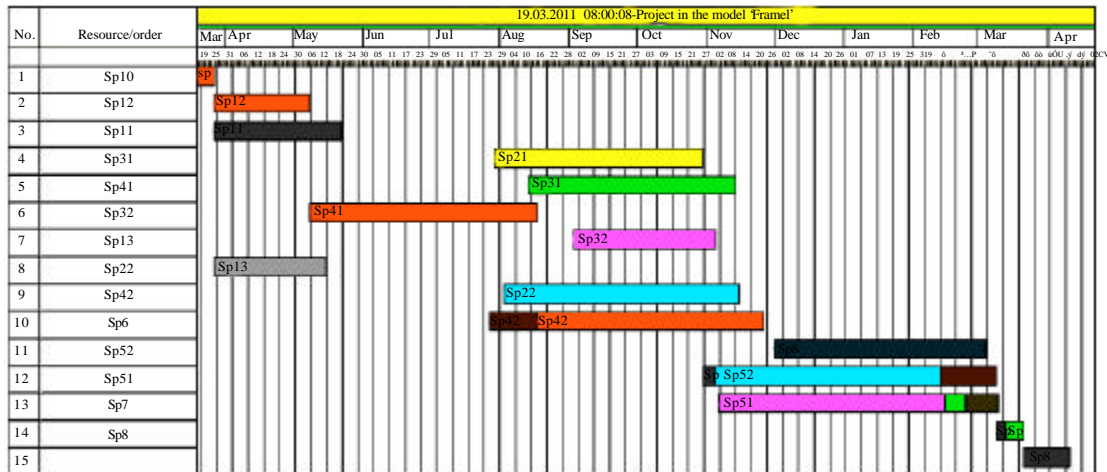


Fig. 3: Gantt chart for LESM project

optimized parameter and the quality-duration-cost collaborative optimization mode is the fitness function.

Result of simulation experiment: The convergence value of fitness is got by simulation optimization (Fig. 2). The x-axis represents the generation number and the y-axis represents the fitness. In the graph, the best solution (red), the average value (green) and the worst solution (blue) are calculated. The best evaluated fitness is 158, 268, 544 Yuan and the Gantt chart for the best solution is illustrated by Fig. 3

CONCLUSION

Lean logistics was integrated into operational planning and control process firstly and the relations of quality, duration and cost were discussed. Secondly, Taguchi quality loss function and penalty factor were introduced to establish a quality-duration-cost relation model based on the cost. Thirdly, a multilevel and multi-objective collaborative optimization model was built. Model algorithm was designed using SM and GA method. And the efficiency of the model and algorithm was testified through the sample study. In conclusion, they lay a theoretical foundation for large equipment enterprises to transform to service-oriented manufacturing.

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