Manufacturing System Design to Improve Quality Buy Rate: An Automotive Paint Shop Application Study

Jingshan Li, Dennis E. Blumenfeld, and Samuel P. Marin

***Abstract*—Manufacturing system design has an impact on product quality. In this paper, we investigate this impact through an application study at an automotive paint shop. Specifically, for repair and rework systems in paint operations, we develop a model to quantify paint quality [in terms of quality buy rate (QBR)] as a function of repair capacity. We show that the QBR can be improved and unnecessary repaints can be reduced by increasing the repair capacity.**

***Note to Practitioners*—Manufacturing system design and quality management are important in many manufacturing industries. Although they have attracted substantial research effort, little attention has been paid to address the coupling or interactions between system design and product quality. Empirical evidence and analytical studies have shown that manufacturing system design does impact quality. In this paper, through an application study at a repair and rework system in an automotive paint shop, we show that paint quality, as measured by the quality buy rate, can be improved by designing the system more effectively. Similar problems are also often encountered in other manufacturing systems. Results obtained in this work, along with other results, demonstrate both the theoretical and practical importance of the analysis of manufacturing system design on product quality, and suggest a largely unexplored, but promising research area.**

***Index Terms*—Automotive paint shop, first-time quality (FTQ), manufacturing system design, quality buy rate (QBR), repair and rework.**

I. INTRODUCTION

A. Motivation

System design and quality management are important elements in production systems. Extensive research and practice have been devoted to design manufacturing systems to increase system throughput, reduce lead time, improve customer demand satisfaction, etc. Correspondingly, a substantial effort has been directed to quality control, total quality management, design for quality, etc. However, little attention has been paid to investigate the relationship between manufacturing system design and product quality. Recent studies have shown that manufacturing system design also has a significant impact on product quality (see [1]–[8] for limited references addressing the impacts on quality through inspection allocations, buffer design, machine speed, batch size, line layout, and work load balancing, etc., and [9] for review and summary).

In manufacturing system design literature, product quality is typically treated as an input parameter, for instance, good part ratio, scrap rate, etc., independent of other design considerations (for instance, layout, capacity, reliability, cycle time, etc.). However, as shown in [9], in many cases, different designs may result in different quality performance, or, in other words, different designs may require different levels of effort in quality control to meet the same quality standards. In this paper, through an application study at an automotive paint shop, we show that product (paint) quality can be improved by designing the manufacturing system more effectively.

Automotive painting is an important element of vehicle manufacturing and an extremely complex process. In order to improve paint quality, repair and rework systems are often used in many automotive assembly plants so that vehicles with defects after color coating are repaired or repainted. The effective use of repair and rework loops provides the opportunity to improve system performance in paint shops and several case studies have been devoted to their design and continuous improvement in terms of system throughput [10], [11]. However, the correlation between paint quality and repair and rework system design in automotive paint shops is less studied.

In addition to the automotive industry, repair and rework are also important parts of production systems in many other manufacturing industries as well, such as semiconductor, electronics, packaging, remanufacturing, process industry, etc. A significant amount of research has been directed to performance analysis in such systems (e.g., [12]–[19]). However, most of them address the issues from the productivity perspective; there is still a need to explicitly and quantitatively analyze the interaction between system design and product quality.

In automotive paint shops, paint quality is typically characterized by first-time quality (FTQ) (i.e., the good job ratio of all first-time processed jobs), and quality buy rate (QBR) (i.e., good job ratio of all jobs). Clearly, the QBR includes those jobs that do not pass the inspection first time, but finally exceed the quality standard through rework. Both FTQ and QBR are important quality measurements and they have been widely used in many manufacturing facilities.

To ensure high quality in paint, a primary activity of the paint shop is to improve FTQ by identifying root causes for defects. Much effort is focused on solutions to correct sources of defects. In addition to focusing on FTQ, it is also important to account for jobs needing repair or rework, even when FTQ is high. Unnecessary repaint may lead to a decrease in QBR, loss of throughput, and waste of labor resource and materials, etc., and, in some cases, reduction of FTQ as well. Therefore, designing the paint system to have efficient repair and rework processes is critical to ensure a desired overall quality, as measured by the QBR, which is the emphasis of this paper.

Therefore, addressing the impact of repair and rework system design on paint quality in automotive paint shops is valuable to the current literature. This paper is intended to contribute to this end. Specifically, we study the QBR of the painting process from the point of view of quantifying the relationship between paint quality and repair capacity. We show that increasing repair capacity can improve the QBR of painting operations and reduce the number of unnecessary repaints.

The remainder of the paper is structured as follows: The repair and rework system in the paint shop is described and the problem addressed is formulated in Section II. A model to calculate QBR is developed in Section III. Section IV introduces the design options and sensitivity analysis in the application study. Finally, the conclusions are formulated in Section V. Due to page limitations, all proofs are omitted and can be found in [20].

II. SYSTEM DESCRIPTION AND PROBLEM FORMULATION

In this paper, we consider a repair and rework system at an automotive paint shop whose structure is illustrated in Fig. 1. Such a layout is typical not only for a paint shop, but also for many manufacturing systems with repair and rework operations. The goal of this study is to obtain a good QBR of the painting operation and reduce unnecessary repaints through effective design of the repair and rework capacity.

Manuscript received August 31, 2005; revised November 15, 2005 and January 1, 2006. This paper was presented in part at the 2005 IEEE International Conference on Automation Science and Engineering, Edmonton, AB, Canada, August 1, 2005. This paper was recommended for publication by Editor N. Viswanadham upon evaluation of the reviewers' comments.

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Digital Object Identifier 10.1109/TASE.2006.872958

1545-5955/$25.00 © 2006 IEEE

Therefore, the key objective here is the QBR rather than capacity utilization or other metrics.

In this system, jobs after painting processes are inspected and the job flow is then split based on the quality measurement. A job is sent to the confirmation station if it has good paint quality. All defective jobs are routed to either component replacement, minor repair, or rework according to the nature and severity of the defects. New parts are exchanged at component replacement, and light defects are fixed at minor repair. Jobs with severe defects are sent to rework process and then back to the painting booths for repaint (i.e., the complete painting process is repeated). After component replacement and minor repair, jobs are inspected again. Specifically, jobs undergoing component replacement are routed to the confirmation station if the quality is good; otherwise, they are sent either to minor repair or to rework and painting booths for repaint. Similarly, jobs exiting minor repair with good quality are transferred to the confirmation station and jobs with unsatisfied quality are routed either back to minor repair again, or to component replacement or to rework. The QBR of the painting process is defined as the good job ratio of all first-time and rework jobs at the painting booths.

In addition, component replacement can typically be finished quickly. Hence, its capacity is not a constraint. On the other hand, minor repair often requires more floor space and involves operations that usually take longer. Therefore, its capacity may be limited. When the capacity of a minor repair is insufficient, the painting process may be blocked. In many cases, such blockage is extremely harmful to painting processes and product quality. Therefore, to avoid this blockage, a typical solution is to reroute those jobs that only need minor repair to the painting booths for repaint. In other words, although little dents or scratches may be the major causes of the defects, the whole vehicle could be unnecessarily repainted.

To analyze this system, the following assumptions are introduced:

1) A job can be reworked or repaired multiple times. No scrapping of jobs is assumed.
2) Constant percentages of good quality jobs are assumed in both painting booths, component replacement and minor repair operations, as well as repaint jobs.
3) All routing probabilities are constant in time. In other words, the probabilities that a defective job should go to component replacement, minor repair, and rework are kept unchanged whether the job is a first-time processed job or multiple-time reprocessed job.
4) First-time processed jobs have a higher good job ratio than reworked jobs.

Remarks:

- Typically, there exists a limit on how many times a job can be repainted (for instance, vehicles usually can be repainted, at the most, three times). However, since in most cases, the rework rate is small, the probabilities that a job will be repainted multiple times or a job has to be scrapped are very small. For example, if 10% or 20% of jobs are reworked for new and repaint vehicles, then roughly less than 0.1% of jobs need to be repainted more than three times. Therefore, introduction of assumption 1) will not lead to a large discrepancy.
- Assumption of constant percentages of good quality jobs (assumption 2)) is used to evaluate system performance on average. In practice, they may change randomly. In this study, we concentrate on the average system performance. The preliminary study shows that it provides an approximation when variability in FTQ is not large. Such analysis can also initiate a simple guideline or starting point for detailed simulation analysis. The study on systems with random FTQ is a topic of future work.
- In many automotive paint shops, the good job ratio of the repainted jobs is frequently lower than that of the first-time jobs. The reason behind this may be due to the duplication of original painting process with inserted rework operations, and additional exposure in a non-dirt-free environment, etc. Therefore, not only do previous problems exist, but also new problems may be encountered. Similar observations can be discovered in many other manufacturing industries as well. Assumption 4) is introduced to represent this phenomenon. However, the analysis introduced in this paper is also applicable to the case of higher repaint quality.

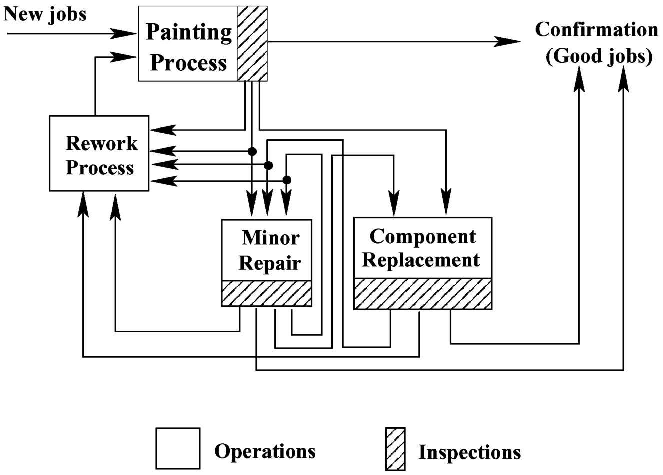


Fig. 1. Illustration of job flow in repair and rework systems in an automotive paint shop.

The problem addressed in this paper is: *Given assumptions 1)–4), develop a method to analyze QBR as a function of minor repair capacity.*

As we introduced before, no explicit quantification of the relationship between QBR and repair capacity has been discovered in the literature. Therefore, we will first develop a model below to describe this relationship, then investigate some monotonic properties which can provide the possibility for potential improvement. Finally, we will discuss the design options and conduct a sensitivity study.

III. MODEL AND ANALYSIS

Consider the repair and rework system shown in Fig. 1. The following notations are used throughout the analysis:

n	number of first time jobs per day;
q	FTQ (i.e., the percentage of good jobs after first processing at painting operations);
q_r	rework quality (i.e., the percentage of good jobs of all reworked jobs that undergo painting operations);
α_x, α_s, α_r	probabilities a defective job should go to component replacement, minor repair or rework, respectively, after painting process inspection;
β_{sx}, β_{ss}, β_{sr}, β_{sg}	probabilities a job goes to component replacement, minor repair, rework or confirmation, respectively, after minor repair;
β_{xs}, β_{xr}, β_{xg}	probabilities a job should go to minor repair, rework or confirmation, respectively, after component replacement;
N	minor repair capacity per day;
Q	QBR of all jobs at the painting process inspection.

By conservation of flow, the following balance equations describe the system behavior:

$$n_r = n(1-q)\alpha_r + n_r(1-q_r)\alpha_r + n_x\beta_{xr}$$

$$+\min(\widetilde{n}_s, N)\beta_{sr} + \max(\widetilde{n}_s - N, 0) \quad (1)$$

$$n_x = n(1-q)\alpha_x + n_r(1-q_r)\alpha_x + \min(\widetilde{n}_s, N)\beta_{sx} \quad (2)$$

$$\widetilde{n}_s = n(1-q)\alpha_s + n_r(1-q_r)\alpha_s + n_x\beta_{xs} + \min(\widetilde{n}_s, N)\beta_{ss} \quad (3)$$

where n_r, n_x, and $\widetilde{n}_s$ are the numbers of total reworked jobs (including multiple time reworked jobs), jobs that go to component replacement, and jobs that should go to minor repair per day, respectively.

In addition, from the total probability equal to 1, the following relationship exists:

$$\begin{aligned}\alpha_x + \alpha_r + \alpha_s &= 1\\ \beta_{sr} + \beta_{ss} + \beta_{sx} + \beta_{sg} &= 1\\ \beta_{xr} + \beta_{xs} + \beta_{xg} &= 1.\end{aligned}$$

The QBR Q of the painting process is defined as

$$Q = \frac{nq + n_r q_r}{n + n_r} \quad (4)$$

where the numerator and denominator define the number of good quality jobs and total jobs per day, respectively.

From (4), a closed formula for QBR can be derived:

Theorem 1: Under assumptions 1)–4), the QBR can be calculated as

$$Q = \begin{cases} \frac{q-(q-q_r)\alpha'_r}{1-(q-q_r)\alpha'_r}, & \text{if } N \geq \frac{\alpha'_s n(1-q)}{1-(1-q_r)\alpha'_r} \\ \frac{nq-n(q-q_r)(1-\alpha_x\beta_{xg})-Nq_r(\beta_{sg}+\beta_{sx}\beta_{xg})}{n-n(q-q_r)(1-\alpha_x\beta_{xg})-N(\beta_{sg}+\beta_{sx}\beta_{xg})}, & \text{if } N < \frac{\alpha'_s n(1-q)}{1-(1-q_r)\alpha'_r} \end{cases} \quad (5)$$

$$\alpha'_s = \frac{\alpha_s + \alpha_x\beta_{xs}}{1-\beta_{ss}-\beta_{sx}\beta_{xs}} \quad (6)$$

$$\alpha'_r = \alpha_r + \frac{\alpha_s(\beta_{sr}+\beta_{sx}\beta_{xr})+\alpha_x(\beta_{xr}+\beta_{xs}\beta_{sr}-\beta_{ss}\beta_{xr})}{1-\beta_{ss}-\beta_{sx}\beta_{xs}}. \quad (7)$$

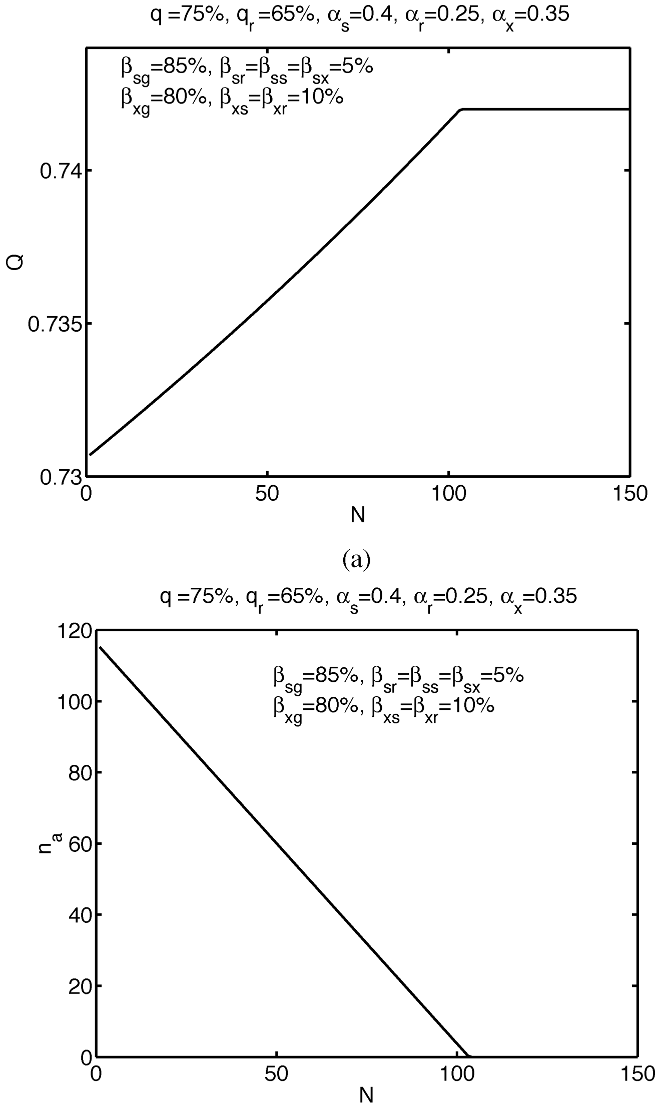
Note that α'_s and α'_r represent the routing probabilities to minor repair and rework, respectively, including the jobs that are still defective after exiting from component replacement and minor repair.

Since the good job ratio of repainted jobs is typically lower than that of first-time jobs (i.e., $q_r \leq q$), it is easy to show that $Q \leq q$ with the equality taking place only when $q_r = q$. This implies that when the capacity of minor repair is insufficient, although rerouting the jobs needing minor repair to rework can reduce the blockage of painting process, it reduces the QBR of painting operation as well. In addition, more painting materials and resources are consumed during the unnecessary repaints. In some cases, it may also lead to a reduction in FTQ since more problems could be introduced during unnecessary repaints. Therefore, to ensure a good QBR, a minor repair should have enough capacity.

In addition to QBR, the number of rerouted jobs n_a (i.e., jobs that should be routed to minor repair, but due to the capacity constraint, are rerouted to rework) is also an important measurement which indicates how much cost savings we may achieve by designing the system more effectively.

Corollary 1: Under assumptions 1)–4), the number of rerouted jobs, can be calculated as follows:

$$n_a = \max\left(0, \frac{n\alpha'_s(1-q) - N\left[1-(1-q_r)\alpha'_r\right]}{1-(1-q_r)(1-\alpha_x\beta_{xg})} \times (1-\beta_{ss}-\beta_{sx}\beta_{xs})\right). \quad (8)$$



(a)

(b)

Fig. 2. Monotonicity of Q and n_a with respect to N. (a) Q; (b) n_a.

Consistent with intuition, we show below that increasing FTQ, rework quality, and minor repair capacity can lead to an improvement in QBR and a reduction in the number of rerouted jobs.

Corollary 2: Under assumptions 1)–4), the QBR Q and number of rerouted jobs n_a are monotonically increasing or decreasing with respect to q, q_r, and N (under insufficient capacity), respectively.

Fig. 2 illustrates how the QBR and number of rerouted jobs change as functions of minor repair capacity. It indicates that the manufacturing system design does impact QBR. As we can see, Q and n_a are monotonically increasing or decreasing when a minor repair does not have sufficient capacity. Q keeps constant when N reaches the size for sufficient repair capacity. However, Q is always less than q if $q_r < q$. To reduce the gap between maximum Q and first-time quality q, increasing rework quality q_r is a choice.

Remark: Corollary 2 implies that the QBR can be improved by increasing the minor repair capacity (given that its capacity is not large enough) even with a lower good job ratio in minor repair. In other words, even when a good job ratio in minor repair is lower than the rework rate, one should still increase the minor repair capacity to improve Q. The rationale behind this is that the number of repainted jobs decreases as the minor repair capacity is increased. Then, from (4), it leads to an increase in Q.

IV. DESIGN OPTIONS AND SENSITIVITY STUDY

In this section, using the model developed above, we analyze the design options and conduct a sensitivity study. For the specific repair and rework system we studied, no jobs after component replacement are routed to minor repair or rework (i.e., $\beta_{xs} = \beta_{xr} = 0$). In other words, only jobs whose defects can be fixed through replacing panels are routed to component replacement. The target daily production volume is $n = 1000$, and routing probabilities are $\alpha_x = 0.25$, $\alpha_s = 0.6, \alpha_r = 0.15, \beta_{sr} = 0.03, \beta_{ss} = 0.05$, and $\beta_{sx} = 0.02$. FTQ is equal to $q = 85\%$, and repaint quality (i.e., rework rate) is characterized by $q_r = \rho q$, where $\rho = 0.6$. (Note due to confidentiality, the numbers introduced in the paper have been modified.)

Two design options are analyzed in this study: small or medium minor repair capacity. In the first option, minor repair capacity is designed as $N = 40$. This option needs less investment and repairing labor. Using (5) and (8), we obtain $Q = 81.37\%$ and number of rerouted jobs $n_a = 87$. The second option is to increase the minor repair capacity, say $N = 80$, which needs more investment and labor. In this case, we have $Q = 83.03\%$ and $n_a = 32$.

Comparing these two options, we can see that by selecting the medium minor repair capacity, the QBR has been increased by 1.66% and the number of rerouted jobs has decreased by more than 60%. Although the investment cost and repair workforce for additional repair capacity may increase, the cost of repainting a vehicle is significantly higher than repairing one. Therefore, we obtain savings by reducing unnecessary repaints, material consumption and rework resources, as well as improvement of quality and throughput. In particular, for systems with a large volume of production and high-profit products, the long-term impact of this improvement will be significant (for instance, for a 1000-jobs daily capacity paint shop, a 1.66% improvement in QBR implies about 16 more good quality vehicles are produced per day or approximately 4000 vehicles per year). The precise decision making will depend on a detailed cost analysis and will be process specific.

Remark: In practice, the study introduced above provides an average quality performance for high-level analysis. Discrete event simulation analysis should be carried out after the study to obtain detailed implementation procedures and parameter settings. For example, increasing the minor repair capacity can be implemented through installing additional equipment or resources, sharing resources with other under utilized subsystems (e.g., component replacement), extending working hours with increased buffer space, etc., depending on specific system configurations and conditions.

Following the design of the system, a sensitivity study is conducted. In this paper, the sensitivity analysis of option 2 is introduced. First, we study sensitivity with respect to perturbations in FTQ and rework quality. Here, we consider the cases of 5% change in q and 10% change in ρ (where $\rho = q_r/q$). The final results are shown in Table I. Based on these results, we conclude that the system performance is practically insensitive to q_r, but it is quite sensitive to q. Therefore, maintaining high FTQ is the key to obtain a desirable QBR. This relies on a more active involvement of process improvement, quality control, root cause analysis, etc.

In addition, we investigate sensitivity with respect to production volume (i.e., variations in n). As shown in Table II, Q is not too sensitive to capacity n. However, if more production volume is required, additional minor repair capacity will be helpful to achieve high QBR.

TABLE I
SENSITIVITY WITH RESPECT TO q AND q_r

	$q = 80\%$	$q = 85\%$	$q = 90\%$
$\rho = 0.5$	$Q = 75.12\%$ $n_a = 94$	$Q = 82.03\%$ $n_a = 39$	$Q = 89.18\%$ $n_a = 0$
$\rho = 0.6$	$Q = 76.44\%$ $n_a = 83$	$Q = 83.03\%$ $n_a = 32$	$Q = 89.35\%$ $n_a = 0$
$\rho = 0.7$	$Q = 78.37\%$ $n_a = 67$	$Q = 83.65\%$ $n_a = 28$	$Q = 89.52\%$ $n_a = 0$

TABLE II
SENSITIVITY WITH RESPECT TO n

	$n = 800$	$n = 1000$	$n = 1200$
Q	83.93%	83.03%	82.46%
n_a	4	32	61

V. CONCLUSION

In this paper, the impact of manufacturing system design on product quality is studied through an application study of repair and rework systems at an automotive paint shop. We develop closed-form expressions to calculate QBR through given repair capacity, FTQ and routing probabilities. We show that paint quality (in terms of QBR) at the painting operation can be improved and unnecessary repaints can be reduced by increasing the minor repair capacity. This result, along with other studies, provides convincing evidence that manufacturing system design does have a significant impact on product quality as well as other factors.

The results presented in this work are not limited to automotive paint shops, but are applicable to other manufacturing systems with repair and rework as well.

ACKNOWLEDGMENT

The authors thank the Editors and anonymous reviewers for their constructive comments and suggestions.

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Social Foraging Theory for Robust Multiagent System Design

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***Abstract*—An analogy between an agent (e.g., an autonomous vehicle) and a biological forager is extended to a social environment by viewing a communication network as implementing interagent sociality. We first describe engineering design within an evolutionary game-theoretic framework. We then explain why sociality may emerge in some environments and for some agent objectives. Next, we derive the evolutionarily stable design strategy for an agent manufacturer: 1) choosing whether the agent it produces should cooperate with other agents in a search problem and 2) choosing the group size of a multiagent system tasked with a cooperative search problem. We show the impact of "agent relatedness," a measure of common descent between two agents based on their underlying manufacturers, on the choices in scenarios 1) and 2). Our predictions are evaluated in an autonomous vehicle simulation testbed. The results illustrate a new methodology for manufacturers to make robust, optimal choices for multiagent system design for a given set of objectives and domain of operation.**

***Note to Practitioners*—The design of autonomous multirobot systems with various applications, such as in parts production or search and destroy operations in a military environment, is of growing importance. Here, we integrate economic and technical issues into an unified engineering design framework for the manufacturers of robots. Our approach leads to manufacturer design decisions that are robust relative to the market for a manufacturer's products. Robot component aspects, such as sensors and communications as well as mission performance aspects, can be captured and coupled into the design process. We use the design of intervehicle cooperation and robot group size to illustrate this approach. The practical significance lies in the fact that we take a broad perspective on engineering design, one closer to the real world, due to the considerations of marketplace economics. Moreover, the approach provides a framework to study design choices that escape systematic analysis in other frameworks (e.g., group size).**

***Index Terms*—Agent, autonomous vehicle, cooperative control, design, evolution, evolutionarily stable strategy (ESS), foraging theory, group size, manufacturer, multiagent, social.**

I. INTRODUCTION

There is a considerable current interest in "cooperative control" for multiagent systems. One area is cooperative robotics where, for instance, cooperative task allocation is studied [2]–[4]. This work, however, focuses on the design of an agent's decision-making strategy, emphasizing 1) reaction to different situations in its domain of operation and 2) the design of strategies that perform well while operating in real time. Rather than study the design of similar strategies, we assume such a strategy is in place and examine the cooperative/noncooperative and group size design choices for the manufacturer. We integrate economics into engineering design to make high-level, mission-planning-type choices (e.g., team composition), not decisions that

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Manuscript received February 25, 2005. This work was supported in part by the Air Force Research Laboratory Air Vehicles Directorate (AFRL/VA) and Air Force Office of Scientific Research (AFOSR) Collaborative Center of Control Science under Grant F33615-01-2-3154 and in part by the Ohio Space Grant Consortium Fellowship. This paper was recommended for publication by Associate Editor Y. Narahari and Editor N. Viswanadham upon evaluation of the reviewers' comments.

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Digital Object Identifier 10.1109/TASE.2006.872124

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