Journal of Engineering and Technology Management, 10 (1993) 285-306
Elsevier

Developing new manufacturing processes: A case study and model

Joseph P. O'Hara, Howard E. Evans and Terry F. Hayden

IBM Corporation, Technology Products, Austin, TX 78758, USA

Abstract

New product requirements may be stimuli for initiating the development of improved tools and processes for manufacturing. Following a well-defined, flexible development methodology facilitates transforming these requirements into tools and processes. The need for enhanced fine-pitch solder interconnection in electronics manufacturing serves as a useful vehicle for viewing the application of one specific development methodology. A detailed description of this methodology is illustrated by following its implementation to achieve a solution for the fine-pitch solder interconnection problem: viz., forming reliable, cost-effective soldered interconnections between new, miniaturized electronic components and printed circuit board surfaces. The resulting attainment of an effective new tool and process set solving the manufacturing problem demonstrates the value of the methodology in the electronics industry. It also indicates its usefulness as a specific framework for empirical studies of future development activities in other industry settings.

Keywords: Process development; Concurrent engineering; Manufacturing; Electronics; Teams; Case study

1. Introduction

Traditionally, new concepts have been transformed into products as the result of often lengthy development cycles wherein the concept is serially worked by a number of diverse groups or functions (e.g., research, marketing, development, quality assurance, product engineering, manufacturing, etc.). The serial approach to development has been frequently discussed (see, for example, Souder, 1987). Progress along such a serial course is typically characterized by a "throw-it-over-the-wall" approach as the new concept is passed from function to function. Serially performed work in any one function frequently fails to take into consideration aspects that may impact subsequent work. Delays and repetitions are not uncommon as each succeeding group attempts to deal

---

Correspondence to: Dr. Howard E. Evans, IBM Corporation, Technology Products, 11400 Burnet Road, Austin, TX 78758, USA.

Elsevier Science Publishers B.V.

with the development work (design, materials selection, process definition, etc.) done by preceding, unrelated groups. New products and manufacturing processes developed in this fashion are frequently suboptimized; in fact, the result may not even fully match the original intent or need. Also, a serial approach to development typically requires excessive time and resources. This serial development methodology has been likened to a "relay race" approach, not consistent with the requirements of today's competitive marketplace. A more efficient and effective methodology has been characterized as a "rugby" approach to development, "where a team tries to go the distance as a unit" (Takeuchi and Nonaka, 1986).

Market success in today's competitive environment requires a complete, efficient development process that yields the right product on the first attempt (Bower and Hout, 1988; Peters, 1990). Innovative concepts alone can be unsuccessful in the marketplace if the materials and manufacturing processes used yield products that are costly, unreliable or of poor quality. Even innovation coupled with high quality can fail if product introductions are unreasonably delayed, sometimes if only by a few months. This environment places the onus for success squarely on the procedures and practices used to turn innovative concepts into manufacturing processes and products. These procedures and practices (i.e., the business processes for responding to marketplace opportunities and for introducing new products) make up what is frequently referred to as the development process. Outdated development processes are recognized as detrimental to U.S. competitiveness (Berger et al., 1989).

The development process guides product and manufacturing development activities. It helps to define interactions between functions and organizations. It can establish the hierarchy and timing of activities ranging from conceptual design to manufacturing line debug. It may also outline quality objectives and assurance procedures. Just as a final product is fixed by the materials and manufacturing processes used to produce it, so, in turn, is a manufacturing process shaped by the procedures (development process) used to develop it.

This paper presents a multi-phase model as a valuable framework for exploration and discussion of issues arising during development. The model promotes a disciplined yet flexible, team-oriented, concurrent approach to new product/process development. Following that description a case study will be presented to demonstrate the development process model's effectiveness in facilitating technological innovation and technology introduction. The case study is drawn from electronics assembly operations in the computer industry.

2. Development process model

The development process, as introduced above, is a framework that defines the nature and structure of all development activities (Dwyer and Mellor, 1991;

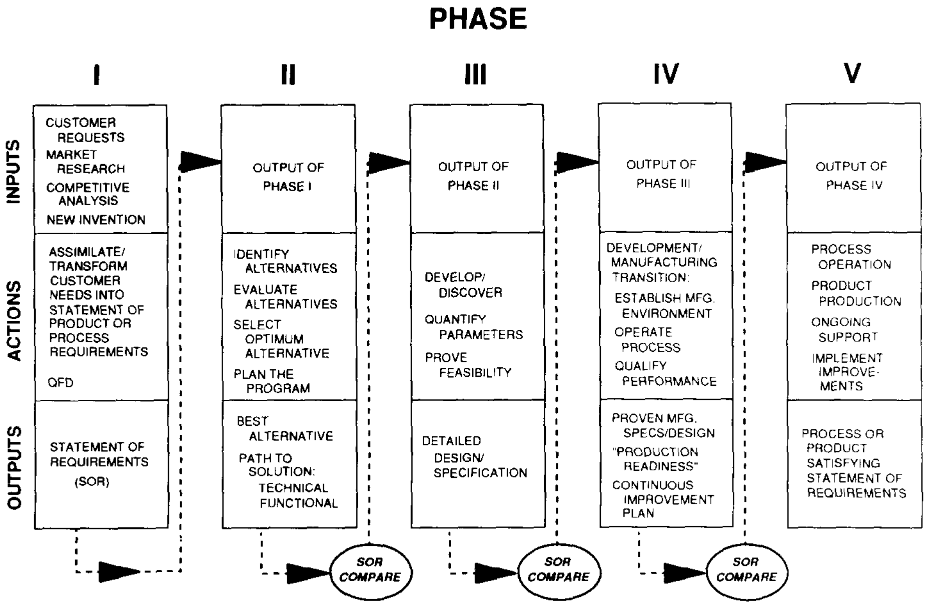


Fig. 1. Model of development process.

Rosenau, 1990). Organizational structure, interfunctional relationships, the nature and sequencing of events and activities, as well as other key items, are all constructed according to the blueprints provided by the development process.

The development process is typically described as a number of sequenced phases, each phase including a set of activities or actions to be completed before the next phase is entered. Various authors have used anywhere from four to twelve phases to characterize the development process (Khan, 1991). The development process model described here is made up of the following five phases: Initiation (Phase I), Concept and Path Definition (Phase II), Concept Validation (Phase III), Refinement and Verification (Phase IV), and Production and Support (Phase V). Each phase is made up of three elements: inputs, actions, and outputs. Inputs are used to initiate phase activities. Actions define the tasks and operations to be performed or accomplished using the phase inputs. Outputs are the direct results of successfully completing phase actions.

A brief description of each of the five phases follows. A summary of the phases, and their inputs, actions and outputs, is listed in Fig. 1, which also schematically shows the relationships between phases.

2.1. Phase I: Initiation

The inputs to Phase I come from a variety of sources. Inventions, requests or suggestions from customers, and market research can all stimulate the identification of new product possibilities. Bacon and Butler (1988) discuss this fully in their treatise on new product origination.

Additional market investigation and analysis (including quality function deployment, QFD (Hauser and Clausing, 1988)), early prototyping and experimentation, and concept detailing are the activities that transform Phase I inputs into a specific and detailed statement of requirements (SOR) for the proposed new project. Such statements may include a description of desired function, plus strategic and financial objectives that must be met. The SOR becomes the output of Phase I, and also serves a key role in keeping later phases on track. This "check-and-balance" role will be discussed later.

2.2. Phase II: Concept/path definition

The input to Phase II is the SOR generated as the output of Phase I. The actions of Phase II include defining the alternative methods and concepts that may provide solutions matching the SOR. Evaluation of these various possibilities results in the identification of a preferred alternative. Maintaining objectivity during evaluations and comparisons can be facilitated by the specificity and completeness of the SOR. The SOR provides a dispassionate measure for assessment. If "political" considerations are important, they can be included in the SOR. For example, it may be deemed important in some projects that the new product or process be proprietary. This requirement would then just become another part of the SOR against which potential alternative solutions are compared. The preferred alternative would meet this, as well as all other, specified criteria.

Based on an identified preferred alternative, a detailed path (or plan) is constructed to reach the desired technical solution. Along with experimental and technical plans, a project management structure is also designated, the purpose of which is to facilitate achievement of all project objectives. Thus, the structure is customized to address each project's specific technical, financial and marketplace objectives.

The project development team (Rosenau, 1990; Reiner, 1988) is one key aspect of forming the project management structure. This team establishes schedules, resource requirements, and test strategies, and delineates other items required to produce a solution matching the original SOR. The result of these activities is the identification of a preferred concept alternative for meeting the SOR, and a defined pathway (or plan) for pursuing that preferred alternative. These are the outputs of Phase II.

2.3. Phase III: Concept validation

Detailed plans from the output of Phase II become the inputs to Phase III. Phase III actions consist of implementing these plans, demonstrating both the feasibility of the preferred alternative and its effectiveness in meeting the requirements defined in Phase I. Any problems associated with the concept are identified and resolved. All key features are investigated and characterized. The resultant output is a complete specification or design for the new process and/or product.

2.4. Phase IV: Refinement and verification

The designs and specifications from Phase III (the inputs to Phase IV) are ready to be established and evaluated in a manufacturing environment.

New tools, processes and/or materials are set up. Operators are trained in all new procedures. Any remaining technical problems resulting from the transfer to a manufacturing area are resolved. Products produced in this manufacturing setting are tested against previously specified performance criteria—successful results demonstrating that all objectives have been met. Finalized designs and/or specifications can now be confidently released for actual production. Manufacturing plans are finalized for process control, capacity expansions to meet anticipated future demands, continuing yield improvements, and other associated factors. Project status at this juncture—the output point of Phase IV—can best be characterized as "production readiness".

2.5. Phase V: Production and support

Actions are initiated directly from the Phase V inputs. Production readiness translates now to full-scale production, with accompanying maintenance and ongoing operational control. Plans for yield improvements and capacity expansions are implemented. The resultant output is the on-schedule availability of products meeting the requirements defined in Phase I, including quantities, quality, functionality and cost objectives.

As shown in Fig. 1, there are three points about the overall model that should be emphasized. First, continuity between phases is facilitated by making the outputs from one phase become the inputs to the succeeding phase. The necessity for achieving continuity has been discussed by a number of authors (Tatum, 1990; Daniels and Waddell, 1991; Dozier and Yacovitch, 1990; Anastasio and Miller, 1991). This need for continuity, however, has to be carefully balanced by control that provides consistency (the second point). Failure to meet final objectives is frequently the result of not completing some of the defined actions in one or more phases. Thus, sufficient control must be maintained to ensure that each phase's outputs have been achieved by successful implementation of the defined phase actions. Also, the phase outputs are then checked for consistency against the SOR output from Phase I. Meeting these complementary requirements—completing all actions, and checking outputs for consistency with project objectives (SOR)—allows the project to move forward into the next phase. The overall development process then becomes the sum total of five phases; their individual inputs, actions and outputs; and the interphase checkpoints ensuring consistency and completeness.

The third point is key to understanding the true nature of the model. The presentation of the model in terms of distinct phases should not be equated with the old "relay race" approach. Rather, the model phases represent successive portions of the "track" or "field" that must be traversed in going from start to finish.

Implementation of the model automatically results in the "rugby team" approach, with all pertinent skills joining together as a team throughout the length of the project. The development process model provides a framework, guidelines, boundaries and goals which the development team uses to construct a customized development project. This self-contained customization feature allows the model to be applicable to both small and large development projects across a wide range of industries. Also, the model responds effectively to project requirements independent of their source. Thus it is applicable to the entire range of requirements from those commonly characterized as "customer pull" to those designated as "technology push".

3. Case study

3.1. Background

An example of the successful implementation of this development process model comes from the computer electronics industry. A major emphasis in the industry is miniaturization, or making products more compact while maintaining or increasing function and performance. A key element of miniaturization is electronic packaging: the interconnecting of various electronic components to produce a functioning unit. Such assemblies are typically effected by soldering individual electronic components onto circuit boards having preprinted interconnecting circuitry (printed wiring boards, or PWBs). Traditional electronic components have had metal leads spaced 0.1 inch apart for soldering to PWBs. There has been a migration during the past few years to technologies using more closely spaced leads as component sizes have been shrunk to meet the demands of miniaturization. Component lead spacings (or, lead pitches) of 0.05 and 0.025 inch are now regularly encountered in the electronics assembly industry. Also, even finer pitches are being used in some applications, and 0.01 inch pitch is expected to be commonplace in the near future.

Such so-called fine-pitch technology requires innovation in several areas of electronics assembly, including: component handling and lead forming equipment, vision-assisted tools for component locating and placement, and materials and processes for forming interconnections (Mullen, 1989; Martel, 1988;

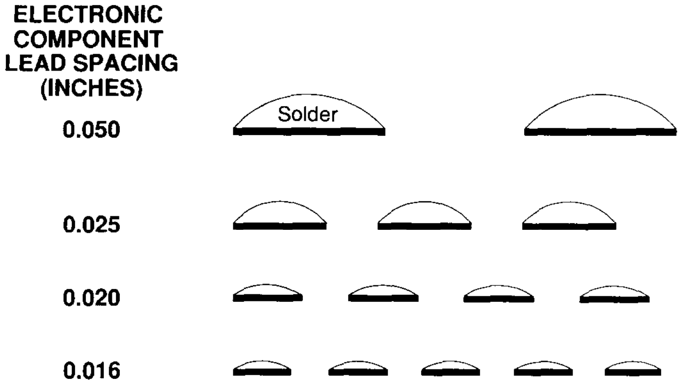


Fig. 2. Schematic representation of effect of miniaturization on component lead spacing and solder application for PWBs.

Prasad and Aspandiar, 1989; Marcoux, 1989). For solder interconnection processes the most challenging (and technologically limiting) step is, perhaps, solder application. The dimensional challenges are diagrammed schematically in Fig. 2. Solder application processes currently used for 0.1 to 0.025 inch pitch components are much less effective for finer pitches. Alternate proposed methods include potentially higher costs or other prohibitive factors.

The intent of this case study is to show how the above development process model was utilized to efficiently and effectively produce a new manufacturing method for fine-pitch solder application. The focus is not on the scientific and technical details of the new process but, rather, on the mechanisms and procedures used to change a "business need" into a new manufacturing operation.

3.2. Phase I

The drive toward product miniaturization was the market input initiating this project (i.e., the input to Phase I), delineating a need for an assembly process that could support the attachment of fine-pitch components. It was determined that tooling for handling and placing fine-pitch components was available, and that the basic problem limiting fine-pitch usage was the ability to effectively perform attachment of the components to PWBs. The attachment procedure is comprised of two basic operations:

(1) application of solder to pads on the PWB; and

(2) the melting and subsequent solidification of the solder on each pad around the component lead, effectively securing the component to the PWB.

Within this process, it was determined that the limiting operation was the application of solder to the closely spaced pads on the PWB. Thus, the "need" was determined to be a means for improved solder application to fine-pitch pads on printed wiring boards. This realization stimulated a series of actions aimed at transforming this generalized need into a detailed set of specific requirements and objectives, as follows:

- Business considerations provided specific cost targets, and also stipulated that any new processes be compatible with existing processes and not disrupt current production when implemented. These latter constraints dictated that soldering processes be used for fine-pitch components while precluding major rearrangements or modifications of existing production lines or equipment. Additionally, any new solder application method had to be flexible enough to handle a variety of potential new component types and products.
- Quality and reliability considerations led to detailed requirements for the amount of solder to be applied, the variability allowed in that solder volume, and the allowed levels of compositional variations in the solder material as applied.
- Manufacturing considerations assigned specific targets for process yields and throughputs. Also, the ability to reapply solder a number of times to the same site was designated as a requirement for a new process. (Such rework operations are necessary for replacing defective components, for example.)
- Finally, the objectives specified that a new process must be consistent with pertinent environmental constraints and strict safety standards.

The original need was identified as designers of a new product, working with miniaturized electronic components, interacted with engineers planning for the manufacturing implementation of new products. Successfully transforming a recognized need into a detailed SOR requires input from an entire range of business and technical functional perspectives. Under guidance of a project leader, individuals whose skills represent the various pertinent functional per-

TABLE 1

Alternatives evaluation matrix

Project requirement (SOR)	Method A	Method B	Method C	Method D	Method E
Solder uniformity	⇓	⇓	⇒	⇑	⇑
Solder sufficiency	⇓	⇒	⇑	⇑	⇒
Cost/throughput	⇓	⇒	⇓	⇓	⇒
Yield	⇒	⇓	⇓	⇑	⇑
Flexibility	⇓	⇓	⇓	⇓	⇑
Rework options	⇓	⇓	⇓	⇓	⇑
Manufacturing impact	⇓	⇑	⇓	⇓	⇓
Environmental impact	⇓	⇒	⇓	⇓	⇒
Amount development required	⇑	⇑	⇓	⇒	⇓

⇑ = favorable, ⇓ = unfavorable, ⇒ = neutral.

spectives are brought together to formulate and detail the SOR. This initial form of a project team evolves to meet the requirements of subsequent phase activities. The designation, structure and evolution of the development team throughout the life of a project is guided by the model. Details of team nature and involvement are beyond the scope of this presentation.

To summarize, involvement by the relevant functions and areas, at this early stage in the project, resulted in a complete listing of project requirements. These are summarized in the left hand column of Table 1. This list is the statement of requirements for the solder application process development project. It is the output of Phase I, the input to Phase II, and the basis for comparison to ensure consistency with each subsequent phase's outputs.

3.3. Phase II

Once a statement of requirements had been produced, Phase II began. The project team structure was expanded to include sufficient resources to complete Phase II activities within a time frame compatible with the SOR. Also, the organizational and technical structures required to perform subsequent process development activities were defined and put in place. In this phase, alternatives to satisfy the statement of requirements were identified and evaluated, and the one alternative providing the best solution was selected to be taken forward into Phase III.

Identification and evaluation of alternative solutions

In this case, the identification of candidate alternatives to meet the statement of requirements—a cost-effective (viz., efficient, high-yielding and repeatable) manufacturing process that could be implemented within a given timeframe, for the application of solder to fine-pitch sites—was reasonably straightforward. There are several well known methods used or demonstrated for the application of solder to PWBs. These known methods, either by themselves or in combination with one another, comprised the majority of the list of alternatives for evaluation.

In addition to exploring alternatives already used or proposed in the industry, another source of alternatives in some companies is the research organization. While the effectiveness of central research organizations in some companies may be limited (Frey, 1989), this particular company's research organization was very much aware of the need to develop fine-pitch solder application technology to support advanced electronic packaging concepts. This awareness was generated during regular review meetings between research and development personnel where plans, needs and capabilities were shared and reviewed. Having a structured means of interaction between research, development, marketing, manufacturing and other functions is imperative if research organizations are to be effectively utilized. Semiannual or annual "working session" reviews can provide information exchange vital to the use and direction of research resources. This research group, for some time, had been assessing a novel solder application concept and was alert for opportunities to have this concept developed for a manufacturing environment. Information exchanged with the process development organization indicated that the research concept should certainly be added to the list of alternatives being assessed for possible development into a manufacturing process.

The next step was to evaluate and compare listed possibilities so as to determine the alternative with the best chance of meeting the desired objectives (as summarized in Table 1). Currently practised techniques had to be explored to determine if they could be adapted or extended to the situation at hand. For example, the process of solder paste screening or stenciling is common industry practice for applying solder to PWBs, including 0.025 inch pitch applications. The evaluation of this method's applicability then became an analysis of the feasibility of extending the stenciling process to smaller dimensions and tighter tolerances. Similarly, the evaluation of other well-known alternatives—hot air solder leveling, electroplating of lead/tin, using a modified wave solder process, etc.—involved both paper studies and experimental work to determine whether these techniques could be extended, enhanced or combined to best satisfy the SOR. A complementary assessment of the research-proposed concept was also included.

To determine the final selection, comparisons were undertaken (involving both analytical and empirical investigations) with the intent to select the optimum alternative. Table 1 summarizes the key elements of the statement of requirements from Phase I and a relative, qualitative assessment of how the various alternatives met these elements. There were five possible alternatives identified which are referred to as Methods A through E in Table 1. A technical discussion of these methods is not critical to understanding the selection process and subsequent development activities. Note, also, that Table 1 schematically illustrates the evaluation results in a qualitative manner, while the actual comparisons were quantitative. An "up-arrow" for a given alternative indicates that the attribute was considered a point in favor of the alternative. Similarly, a "down-arrow" indicates a negative consideration. A sideways arrow indicates a neutral stance. It can be seen from the table that none of the alternatives provided a perfect solution. However, Method E, the research concept, was deemed to be the best compromise of risk and reward, and was thus selected as the preferred alternative.

The primary risks were judged to include the significant amount of development required to produce a manufacturing-level tool and process, and the introduction of a new technology into the manufacturing line. The potential reward was a high-yielding, flexible, cost-competitive technique for fine-pitch solder application. Other alternatives, for the most part, are seen to have equally large risks of impact to the existing manufacturing process. While the other alternatives may have required less development (they were, after all, mostly derived from current industry practices), they were determined not to offer the extendibility necessary to meet the majority of the requirements.

Project team considerations

Once the identification of a preferred alternative was complete, it remained to define the other part of the path to satisfying the statement of requirements: the team and structure for performing subsequently defined development activities.

The project team again evolved to meet the needs of the next development phase. The composition required at this point was dependent on the selection of the preferred alternative, since different alternatives required different skill sets. Once Method E had been chosen, it was partitioned into subsystems as shown in Fig. 3. Required technical skills could be determined by examining the nature of each subsystem. Additional team members were then selected based on the number and types of skills necessary for development of the subsystems and their integration into a final product. The technical skills associated with the partitioned system are shown in Fig. 4.

Clearly some of the same skills are required for multiple subsystems. Depending on the extent of the required work in each subsystem, the same individual may provide skills to multiple subsystems. In fact, for the project under discussion, two mechanical engineers, one electrical engineer, one programmer

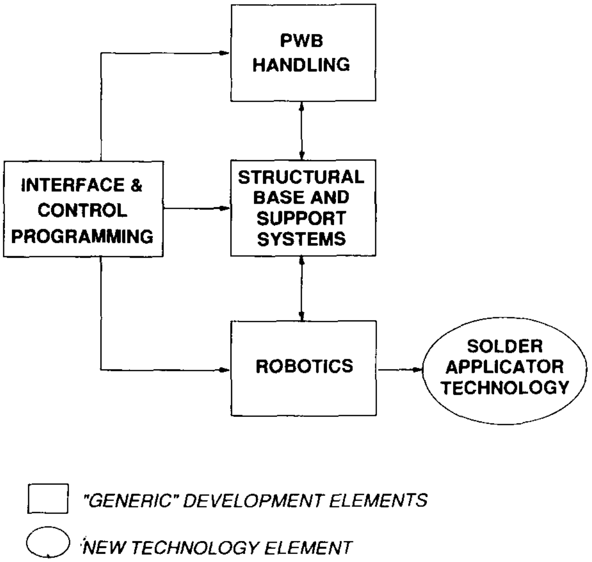
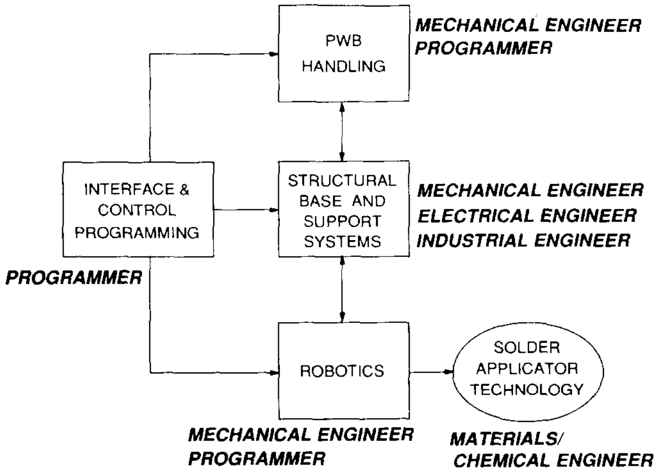


Fig. 3. Partitioning of preferred alternative into subsystems.



ADDITIONAL PROJECT TEAM MEMBERS:

PROJECT MANAGER
RELIABILITY
QUALITY
MANUFACTURING ENGINEERING
LEGAL
FINANCE
ENVIRONMENTAL/HEALTH/SAFETY
PURCHASING
VENDORS

Fig. 4. Team members' skills by subsystem.

and one materials/chemical engineer covered the different subsystems' engineering requirements (with appropriate technician assistance).

Developing and integrating the five subsystems shown in Fig. 3 required some skills in addition to the engineering skills defined above. A key participant is the program manager (see, for example, Randolph and Posner, 1987), who maintains a "big picture" outlook and keeps the overall goals in front of the team. He also assists in "smoothing" the process on a real-time basis by removing roadblocks that could defocus the effort of others on the team. Other key members of the team include manufacturing personnel, who represent the interests of those who will ultimately use and maintain the developed system, and assurance organization personnel, who provide "independent" validation of the reliability aspects of the new tools and processes. Peripheral, but important, areas of involvement included legal, finance, purchasing, and vendors supplying components, services and materials.

When development team members are added, they may require education as to the technical, financial and administrative requirements of the program. Ideally, the number of team members needing such education is limited; often team members have already been involved in the preferred alternative selection process (Phase II) and (in many cases) in defining the original need or SOR (Phase I). Early and continuous involvement of team members has been found to be a valuable factor in ensuring success; it provides continuity in addition to engendering ownership and commitment to the project. There may be, however, team members who were not involved in the selection of the technology. It is the program manager's job to get them fully educated and involved. Once this is done, the team is allowed to determine the development path.

Path definition

In this case study, general guidelines were laid out in terms of schedules and resources; however, the team formulated the technical development plan (specifying experiments, designs, tests and schedules). Guidelines were followed as much as possible, but deviations were made when justified by technical considerations. The program manager is critical here as he must ensure that plans are reasonable and consistent.

Technical development plans were based on the fact that developing some of the subsystems (those shown as boxes in Fig. 3) was fairly straightforward. Subsystems such as the robot and the PWB handling mechanisms did not require extensive new inventions or development; they had been done before and, while they needed to be integrated with the rest of the system, the consensus of the team was that this activity would not pose difficulties. The solder applicator technology (oval in Fig. 3), however, was identified as requiring significant new development to transform it from a research lab model to a manufacturing level. Most of the issues to be addressed involved design and materials considerations to ensure robustness and reliability in a high-volume production environment where minimum maintenance and only limited operator intervention are required. Mindful of this, the team planned its development activities and derived a schedule for the work. With this accomplished, Phase II was completed.

To summarize, Phase II was entered with a statement of requirements. A selection of a preferred alternative from a variety of possibilities was made and, based on the technical demands of the selection, the team was modified and expanded to include appropriate skills. The team put together a development plan for meeting the requirements to provide technical data and designs necessary to demonstrate viability and finalize equipment and process specifications. These items collectively became the outputs of Phase II. As presented above, an interphase "checkpoint" determined whether phase outputs were consistent with the original SOR. This being the case, the project moved ahead into Phase III.

3.4. Phase III

Phase II provided a set of plans that defined the actions of Phase III. These actions focused on technical development, including parameter quantification and optimization leading to a demonstration of the validity of the chosen alternative. Mechanisms for implementing the plans also were available from Phase II activities: the development team was in place, responsibilities were allocated and a program management structure was defined.

The "critical path" to success had been clearly identified as being development associated with the solder applicator. Basic feasibility had been demonstrated, including sufficient data to justify projections that this technological approach could best meet project requirements. However, design refinements, optimized material selections and controllable process parameter specifications were still needed.

The starting point was the solder applicator supplied by the research organization. This applicator was designed around the original research concept and included modifications based on learning that had taken place in the Phase I and Phase II timeframes. Adding manufacturing durability ("robustness"), "usability", reproducibility, and controllability to this feasibility model were the next steps. This development effort necessitated close interactions between the chemical/materials engineer and a mechanical/design engineer, where evolving concepts regarding optimization could rapidly be evaluated. Iterative overnight fabrications followed by next-day process evaluations were conducted during this period. Iterations were based on factorial experiments devised to identify important parameters and features, as well as to confirm that effective means of adjusting and controlling these parameters had been designed into the system. This continued until design and processing conditions were refined to the point where all major features impacting performance were identified, and that the means for monitoring, varying and controlling these features were well understood.

It should be pointed out that the solder applicator was not yet integrated with its manufacturing-level base structure, automation and panel handling equipment. This interfacing and integration would still require design additions and changes to the applicator. These changes, however, would not affect fundamental function or control. It was the partitioning of subsystems—described in Phase II—that allowed work on the functional aspects to be expedited, without waiting for all the "generic" tooling aspects to be integrated together. Development of the "generic" subsystems continued to proceed in parallel, with the program manager facilitating communications to ensure compatibility between subsystems.

Response surface analysis (RSA) techniques, consisting of (quadratic) designed experiments, were used to finalize process parameters. These techniques defined optimum values for all operating parameters identified as having significant effects on the solder application process. Earlier experiments (including those in Phase II) identified and separated the significant process variables and response defects from those that were not critical, using the early model research tool. Phase III RSA experiments now delineated specific trends and sensitivities in these significant variables on the functionally optimized tool. Allowable operating "windows" for each parameter were determined. The set of significant variables plus their acceptable ranges of values became the process specification, a key output of Phase III. (See Montgomery (1988) for discussion of process parameter determination and optimization via designed experimentation.)

Finalized designs for the solder applicator, together with designs, software and controls for the other ("generic") subsystems completed the outputs from this phase. Manufacturing involvement was especially important in arriving at these finalized specifications. Their expertise helped ensure that the new solder application tool could be easily moved into the overall manufacturing line, and that it would be compatible with other existing tools. Manufacturing was also best able to guide the final design into being "operator friendly", durable and easy to maintain. Thus, manufacturing involvement through Phase III greatly facilitated the subsequent Phase IV activities: establishing and operating the new process and tool in the manufacturing area (Souder and Venkatesh, 1989). Following a checkpoint comparison to ensure completion of Phase III activities, as well as consistency between the original SOR and the final design and specifications, the project proceeded into Phase IV.

3.5. Phase IV

The Phase IV objective is to make an effective transition to the manufacturing environment from the discovery and development activities that culminated in detailed specifications (the output of Phase III). For the case at hand, this meant synthesizing the more routine or "generic" elements of the preferred alternative with the element that required significant development work (see Fig. 3).

It was the first order of business, then, in Phase IV to integrate the components into a complete system and perform testing to identify and solve any problems with the final system configuration. This is the period of time when detailed considerations of safety, maintainability and environmental sensitivity were, per previously established plans, integrated into the system and tested. After initial checkout and verification by the engineering team—during which time minor integration problems were addressed—the process was operated by manufacturing operators in a manufacturing environment to provide a demonstration of readiness for production. In cases such as this, where a new process is being introduced, the demonstration of production readiness typically involves two related areas:

(1) Manufacturability: a demonstration that the process meets established performance objectives in terms of yield, throughput, equipment maintainability, etc.

(2) Quality/reliability: a demonstration that the process will support the product's ability to perform its functions for the duration of its specified lifetime.

Typically, the quality/reliability portion of this demonstration of production readiness is not accomplished until (1) the final version of the tool and process are available, and (2) the manufacturability demonstration has been completed. Current electronic assembly reliability evaluations usually involve lengthy periods of stress testing, often taking months to accomplish. The manufacturability evaluation, on the other hand, is often much quicker. It usually involves building a number of parts and computing the effective production rates, yields and equipment performance factors.

This project team was able to identify and take advantage of circumstances that allowed reliability testing to commence while still in the Phase III timeframe (see Fig. 5). Specifically, in Phase II, the team (which included a representative from the reliability assurance organization) determined that product quality and reliability were strong functions of the materials set used (solder, fluxing agent, lead and board materials) but only a weak function of the applicator design. The system performance—yield, primarily—was, however, a strong function of the design and final process parameters. This is why the development efforts in Phase III were focused on design modifications and process parameter experiments to improve yield and "robustness" in the manufacturing environment. The result of this recognition was the agreement that reliability evaluation samples could be produced with other than the final manufacturing-level design of the applicator. It was recognized that the yield of this sample hardware build would not be acceptable, of course, but this aspect would be addressed in the manufacturability evaluation to take place later. Thus, the time-consuming reliability testing could commence while the generic elements of the system were being integrated together with the final applicator design to produce a complete manufacturing tool.

The manufacturability demonstration was conducted, as indicated, after the system had been integrated and assembled in a manufacturing environment. This relatively short demonstration of system performance was based on, among other factors, measured speed and process yield; i.e., the number of good units produced by the process divided by the number that entered the process.

By careful planning and consideration of evaluation activities in Phase II, then, the team was able to identify and take advantage of a situation that allowed for atypical concurrency. This led directly to early initiation and completion of reliability testing with resultant substantial savings in Phase IV development time. The development process model promotes this type of streamlining through early, total-team involvement and planning.

Successful completion of Phase IV was based on the satisfactory demon-

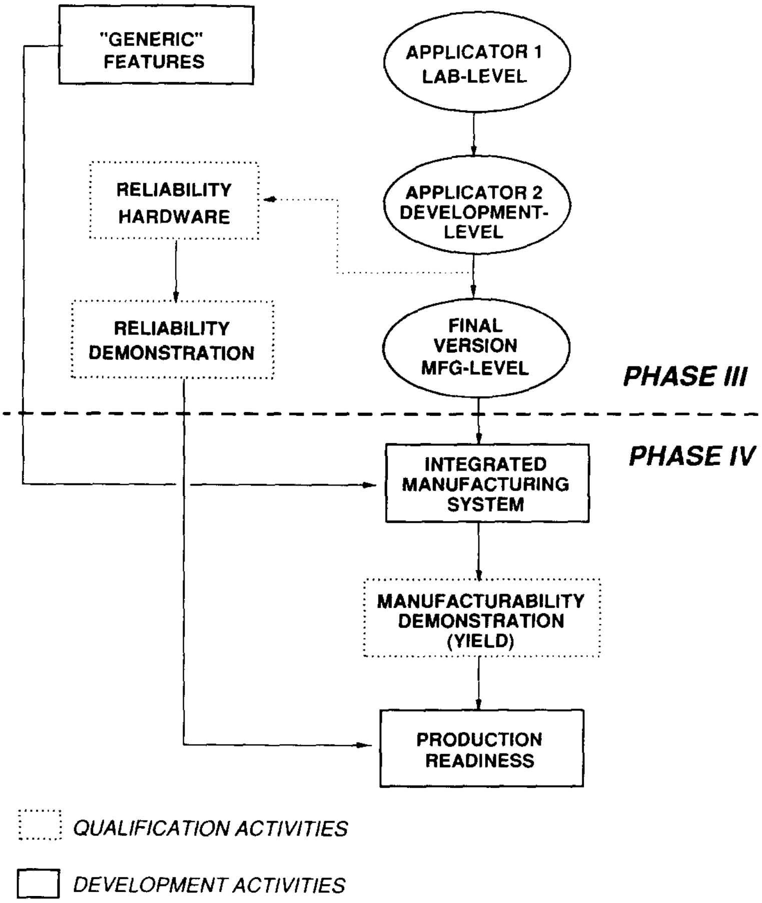


Fig. 5. The integration of generic and critical path features to demonstrate production readiness.

stration of production readiness and the presentation of the team's plan for continuous system/process monitoring and improvement. This plan is necessary to ensure that processes and tools are constantly under control, that anticipated capacity expansions are implemented on time, and that decreasing production cost targets are met. It is clear that the onus for producing such a plan is on the development team, whose members have included manufacturing representatives from the outset.

3.6. Phase V

After ensuring that the outputs of Phase IV (demonstrated production readiness together with plans for ongoing process control, expansion and improvement) are still consistent with objectives delineated in the SOR, these outputs can be transformed into full-scale production (Phase V). Details of Phase V manufacturing activities cannot be represented here since products based on this technology have not yet been announced.

4. Conclusion

4.1. Model and case study summary

The success of new product development efforts is greatly facilitated by following a logically defined path throughout the development process. A development process model has been described, and illustrated with a case study from the electronics assembly industry. As shown in Fig. 1, the model consists of five phases and ensures that each new development project includes certain features generally requisite for successful projects, such as the following:

(1) specific delineation of objectives and statement of requirements (SOR);
(2) consideration of all possible alternatives, and systematic evaluations leading to the selection of a preferred alternative;
(3) the formation of a development team based on skills needed for the specific project;
(4) identification of all key technical elements of a project, and formulation of experimental plans to determine and specify all pertinent design and process parameters;
(5) structuring a detailed project plan including objectives, checkpoints, interactions, responsibilities, etc.;
(6) ensuring and verifying manufacturability of new processes and tools;
(7) assurance and verification of product quality and reliability;
(8) demonstration of "production readiness", and a smooth transition from development to manufacturing.

While providing specific guidelines for developing new processes and products, the model described above also promotes flexibility to ensure maximum benefits can be achieved in minimum time. All of the above points are illustrated in the case study.

The study described some of the challenges in electronics assembly technology attendant to the continuing miniaturization of electronic devices and increases in performance-to-size ratios. A need for improved solder application methods drove a series of development activities (as guided by the model) and culminated in a new tool and process being successfully integrated into the manufacturing line. The model ensured that all important actions were included while allowing a dedicated project team to define the detailed activities. Figure 6 indicates the flexibility of the model in allowing activities to be sequenced in the most opportune order regardless of the model phase with which they are typically associated. Here, time-to-market was minimized by parallel

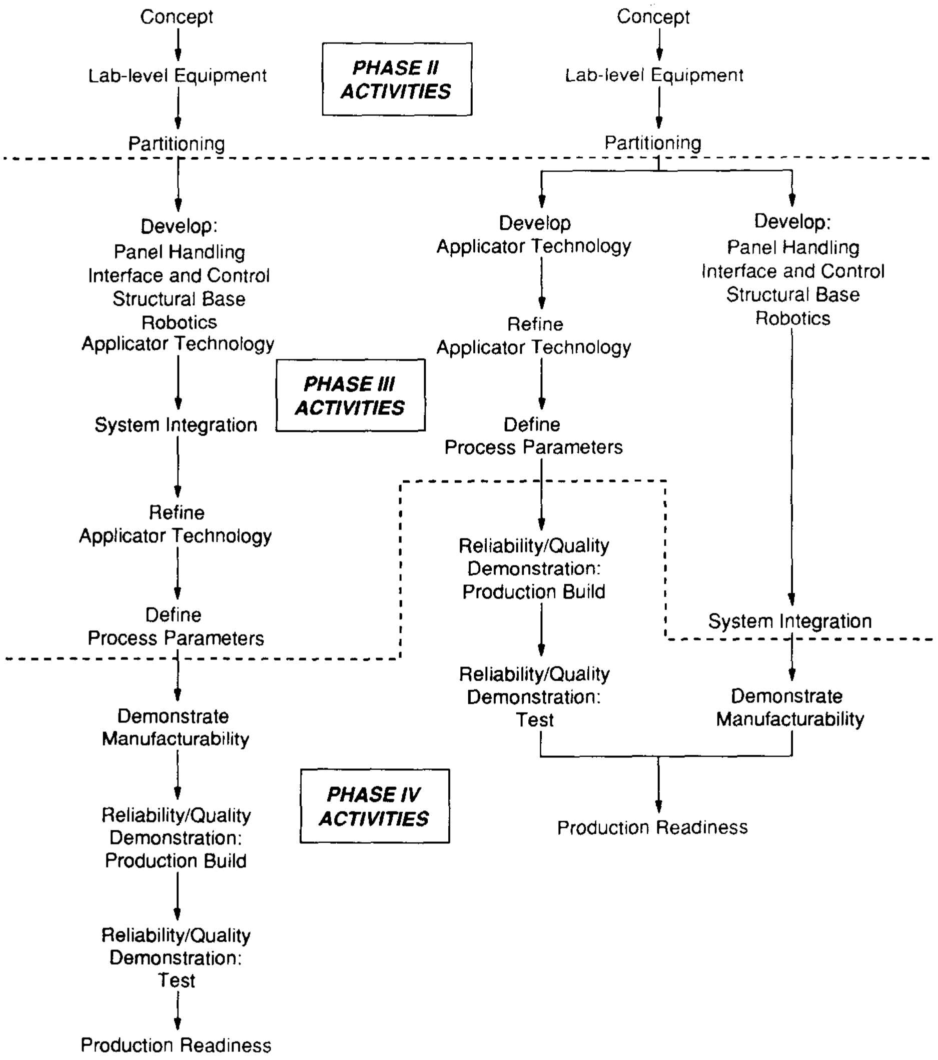


Fig. 6. Comparison of normal linear (left side) and parallel (actual) implementations of key development activities for the case study.

development activities in a number of areas. Partitioning of the applicator development activities (where the key function of the tool resided) from the "generic" development activities enabled concept validation to occur without delays imposed by a serial development approach. Similarly, decoupling reliability and manufacturability concerns (in Phase IV) saved time and was made possible by early involvement and mutual understanding and agreements between those representing quality assurance, manufacturing and development perspectives.

4.2. Issues and discussion

The success of this *project* was measured by meeting the technical and business objectives originally defined, resulting in a new process and tool set in manufacturing with capability to effectively and efficiently provide solder application for miniaturized "fine-pitch" electronic components.

The success of the *development process* was determined by comparing the time and resources required for this project to the same parameters required for other similar projects. The project described in this case study required only about 50% of the time and overall resources as did comparable projects. This significant accomplishment in reducing development time and resources was attributable directly to the development process methodology employed: that is, the methodology described in the development process model.

There are ongoing management-related issues that need to be addressed, even after an effective development methodology has been identified. Some of these issues are discussed below:

Deciding which potential projects should be developed. There are generally more opportunities than there are resources. Overcommitting the number of projects undertaken typically results in a large number of projects that each lack enough resources to be successful. Carefully selecting the projects that both fit within resource constraints and also provide the best return on investment is an ongoing management challenge (Wheelwright and Clark, 1992).

Ensuring availability and continuity of resources. One aspect of this is, as described above, avoiding overcommitment of resources. Other aspects involve hiring and retaining the proper mix of skills required, and avoiding moving team members from one project to another before project completion can be achieved.

Truly empowering the development team. Management must maintain communication and facilitate the solution of any problems encountered by the team (frequently resource-related), while at the same time avoid interfering with the empowered team's direction and function.

Educating people in the principles of development methodology. If the methodology is going to work effectively, then those involved must understand their roles, how they relate to other team members and functions, and clearly view the overall "vision" of how development is to be effected. Instilling this vision in the development "implementers" may be the most important key to success once the actual methodology has been defined.

Adapting the overall organizational structure to accommodate the use of interdisciplinary development teams. Most large companies (and many smaller ones) remain organized around functional groupings. While teams can be formed in such organizations by using "matrix" responsibility concepts, a more effective approach may be to change the organization to a team, rather than functional, structure.

Global communication of ideas. Development personnel first became aware of the emergence and potential usefulness of the research concept through such communication vehicles as planned visits, informal phone calls and monitoring of periodic, formal progress reports.

The project described in this case study demonstrates the effectiveness of the development model in a corporate setting. It was pointed out earlier that the functioning of the model is essentially independent of how the project is initiated. That is, the development methodology is basically independent of whether the project is initiated by a customer request or by the desire to find a market for some new scientific discovery or invention. Because the methodology is dependent on empowered interdisciplinary teams, it will be most easily implemented in cultures where team approaches are already accepted and/or practised. The model is not specific to any one industry or product type; in fact, in addition to the case study documented above, it has been effectively utilized in projects ranging from new materials processing to mechanical design. Because the model includes customization by the project team in defining development plan specifics, it can be applied to projects of all types. Also, although the case study occurred in a large integrated corporation (including self-contained research, development, manufacturing and marketing), the customization feature of the model will allow its use in more narrow or restricted venues as well. Applicability and effectiveness, perhaps the most important features to be found in any development methodology, are both features of the model utilized in this case study.

Acknowledgements

The authors acknowledge the valuable contributions of their colleagues in the Thomas J. Watson Research Center, Yorktown Heights, New York; specifically Peter Ledermann, the inventor of the process used in the case study. Also, the contributions of the members of the project team in the Electronic Card Assembly and Test Development Center, Austin, Texas, are gratefully acknowledged.

References

Anastasio, F.J. and Miller, D.J., 1991. Technology development: Focus on manufacturability. *IEEE Trans. Compon. Hybrids Manuf. Technol.*, 14(3): 488-492.

Bacon, F.R. and Butler, T.W., 1988. *Planned Innovation*. University of Michigan, Ann Arbor, MI, 243 pp.

Berger, S., Dertouzos, M., Lester, R., Solow, R. and Thurow, L., 1989. Toward a new industrial America. *Sci. Am.*, 260(6): 39-47.

Bower, J.L. and Hout, T.M., 1988. Fast-cycle capability for competitive power. *Harv. Bus. Rev.*, 66(6): 110-118.

Daniels, R. and Waddell, P., 1991. Design for assembly. *Circuits Assembly*, 2(7): 24-27.

Dozier, P. and Yacovitch, B., 1990. Case history: From spec to Beta Site in three months—Mercury Computer Systems shaves time-to-market of high-density boards. *Surface Mount Technol.*, 4(4): 22-26.

Dwyer, L. and Mellor, R., 1991. Organizational environment, new product process activities and project outcomes. *J. Prod. Innov. Manage.*, 8: 39-48.

Frey, D.N., 1989. Junk your linear R&D. *Chief Exec.*, 49: 54-56.

Hauser, J.R. and Clausing, D., 1988. The house of quality. *Harv. Bus. Rev.*, 66(3): 63-73.

Khan, J., 1991. The development project cycle and a Barbadian project. *Project Manage. J.*, XXI(2): 27-32.

Marcoux, P.P., 1989. Fine pitch technology makes the going tough. *Printed Circuit Assembly*, 3(3): 6-8.

Martel, M.L., 1988. The fine-pitch dilemma. *Circuits Manuf.*, 28(11): 47-50.

Montgomery, D.C., 1988. Experiment design and product and process development. *Manuf. Eng.*, 101(3): 57-63.

Mullen, D.R., 1989. Stretching the limits of surface mount placement. *Electron. Packag. Prod.*, 29(3): 43-48.

Prasad, R. and Aspandiar, R., 1989. Systems manufacturing with fine pitch devices. *Printed Circuit Assembly*, 3(3): 9-14.

Peters, T., 1990. Time obsessed competition. *Manage. Rev.*, 79(9): 16-20.

Randolph, W. A. and Posner, B.Z., 1987. *Effective Project Planning and Management: Getting the Job Done*. Prentice-Hall, Englewood Cliffs, NJ, 128 pp.

Reiner, G., 1988. Cutting your competitor to the quick. *Wall Street J.*, 21 November 1988.

Rosenau, M.D., 1990. Faster new product development: Getting the right product to market quickly. In: *Amacon Proceedings*. American Management Association, New York.

Souder, W.E., 1987. *Managing New Product Innovations*. Lexington Books, Lexington, MA, 251 pp.

Souder, W.E. and Venkatesh, P., 1989. Transferring new technologies from R&D to manufacturing. *Res. Technol. Manage.*, 32(5): 38-43.

Takeuchi, H. and Nonaka, I., 1986. The new new product development game. *Harv. Bus. Rev.*, 64(1): 137-146.

Tatum, C.B., 1990. Integrating design and construction to improve project performance. *Project Manage. J.*, XXII(2): 35-42.

Wheelwright, S.C. and Clark, K.B., 1992. Creating project plans to focus product development. *Harv. Bus. Rev.*, 70(2): 70-82.