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MARK III, A New Approach to High-Variant, Medium-Volume Flexible Automatic Assembly Cells

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SUMMARY

The MARK III FAA (Flexible Automatic Assembly) cell was designed to minimise the risk factors associated with FAA. This FAA cell is stepwise upgradeable and adopts the sub-batch principle and reversed material flow solutions. It allows for the assembly of products with an annual volume normally too low to justify automation. The MARK III FAA cell was implemented with the FACE programming and control system, a PC-based, modular programming and control platform for FAA cells. It enables the management of unpredictable order schemes and leads to very low programming costs.

KEYWORDS: FAA; Sub-batch principle; Reversed material flow; Modular; Task-oriented.

1 INTRODUCTION

The role of FAA cells and systems within modern production systems is clearly becoming more important. Many authors[1, 2] have pointed out that the emerging production strategies are pushing production towards customer-oriented philosophies in which mass-production tactics no longer hold. Such trends have created new operational constraints for FAA cells, thus requiring a revision of their basic requirements. Some of these new trends include:-

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- Increased market competitivity.
- Consistently decreasing product life-cycles.
- Varying product mix.
- Shorter and more reliable delivery times.
- Customer-oriented design and production.
- Increasing number of variants/product.
- Problematic prediction of future production volumes.
- Unpredictable order schemes.
- Increasing demand on high and consistent product quality.

The consequence is that products are now becoming more tailored, leading to a larger product variant flora. The sum of product variants produced is the equivalent, if not greater, than what was once the total volume of a single product. Thus the change from mass producing a fixed range of products to a medium to low volume production of a much wider span of products and variants. The ever decreasing product lifecycles create a greater need for responsive processes. In other words, these new production aspects require flexible processes with inherent adaptability.

The general situation in Europe is that the assembly methods are related to the number of variants per product and yearly production volume (see Figure 1). This figure, a result of a French investigation,[3] clearly points out that there is a gap between manual assembly systems and the so-called IRb assembly lines (typical of Japan). The products affected by this gap are multi-variant products with low-to-medium yearly volumes (particularly relevant in Europe). Companies with this type of production scenario are often small to medium in size and show a definite reluctance in investing in FAA cells due to the risks involved.

In terms of the risk factors associated with FAA

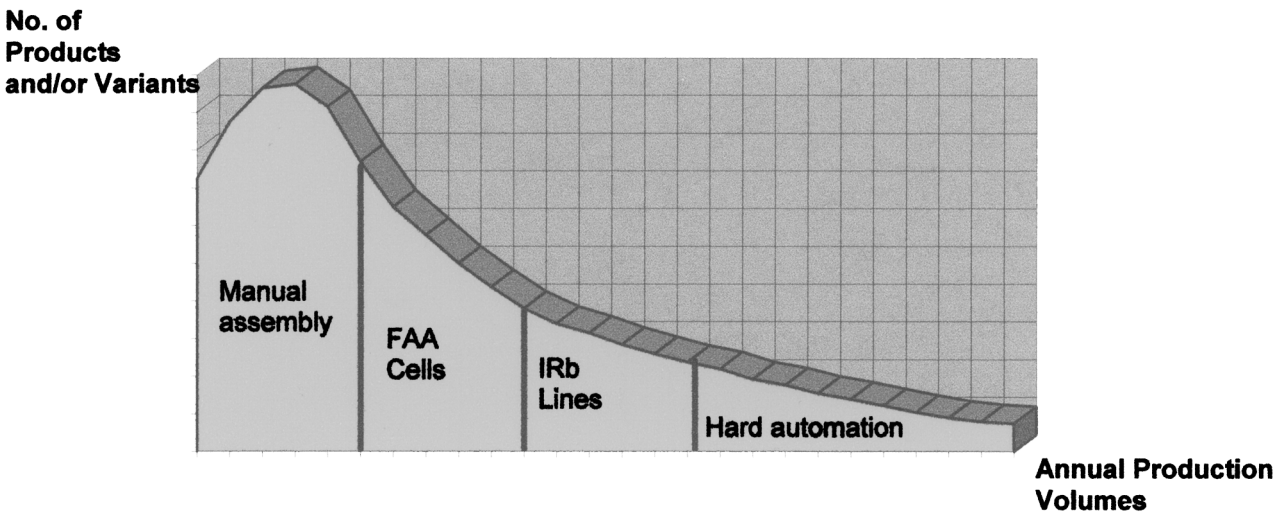


Fig. 1. Volume dependent subdivision of assembly systems

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technology, the remarks are several. FAA cells have, until recently, focused on full automation of both assembly and material flow. They have been termed "flexible" since the developers of such cells have striven to render the FAA cells and systems adaptable to varying assembly situations and tasks. This, however, is only one approach to flexibility since there are issues of re-use and economical adaptivity as well.[4, 5] It is therefore crucial to create FAA cells which simplify the specification demands.

2 TECHNICAL BACKGROUND

2.1 The MARK II FAA cell at IVF/KTH

This FAA cell, first presented in 1987 at the Royal Institute of Technology and IVF (Swedish Institute for Production Engineering Research), described a series of novelties which intended to improve the economical and flexibility aspects of small-batch automated assembly. The MARK II FAA cell was targeted to fulfil the economical requirements of small-batch, low-volume assembly applications. This cell (see Figure 2) introduced the sub-batch principle which led to the following improvements.[6]

- Enables one robot to assemble a large number of part types and product variants.
- Minimal distance between parts-picking and assembly, greatly reducing cycle times.
- Reduced time loss due to gripper exchange compared to conventional robot assembly.
- A feeding concept allowing high density standard feeding units.
- Minimal change-over times.

Two products were assembled with this FAA cell: an air motor from Atlas Copco Tools AB and a steering mechanism from Morse Controls AB. The programming and control was carried out in conventional manner: via the robot controller. A vision system and PLC were used. This resulted in very complex ARLA™ programs in which only the sub-batch size could be selected.[6] It did not account for true order-driven process control. The feeder costs were kept low due to the fact that vision-picking was used extensively.

Initially, the programming cost was estimated at approximately $37,500:- USD.[7] The resulting cost was of $89,000:- USD (excluding hardware).[8] It became well obvious that the risk factor for cost miscalculations using conventional programming techniques was very serious (Figure 3).

2.2 The MARK IIF FAA Cell at ATLAS COPCO Tools AB

The MARK IIF FAA cell represented an industrial application of the principles demonstrated by the MARK II FAA cell. This FAA cell was built at ATLAS COPCO, Tierp, by Electrolux Industrial Systems. Using the sub-batch principle mentioned earlier, it consisted of a SCARA-type robot (ADEPT™) and differed in its equipment to the MARK II. The parts flow was carried out by a paternoster (vertical carousel) instead of the double conveyor system of the MARK II cell.[9] The fixture conveyor was substituted by an indexing table with two sets of 8 fixtures; i.e.- sub-batch size of 8. At the outset (1991) the MARK IIF cell was built for the automatic assembly of 43 variants of an air motor (1 product, 43 variants). This was later expanded to 60 variants (1995). Since the robot used was an ADEPT™ with the V+™ programming and control system, it ws believed to simplify the programming task. V+™ represented (1991) the leading edge of robot controller programming systems and utilised textual off-line programming tools, multi-tasking and database techniques.

The cases described pointed out that recurrent costs such as material flow, feeders, and programming and control remained risk-intensive areas. The sub-batch principle optimised the automatic assembly process and reduced feeder costs, but could not, in itself, achieve a reduction of the recurrent costs.

What also became apparent was the link between programming requirements and control strategies. If the programming of the process tasks is not rendered simple

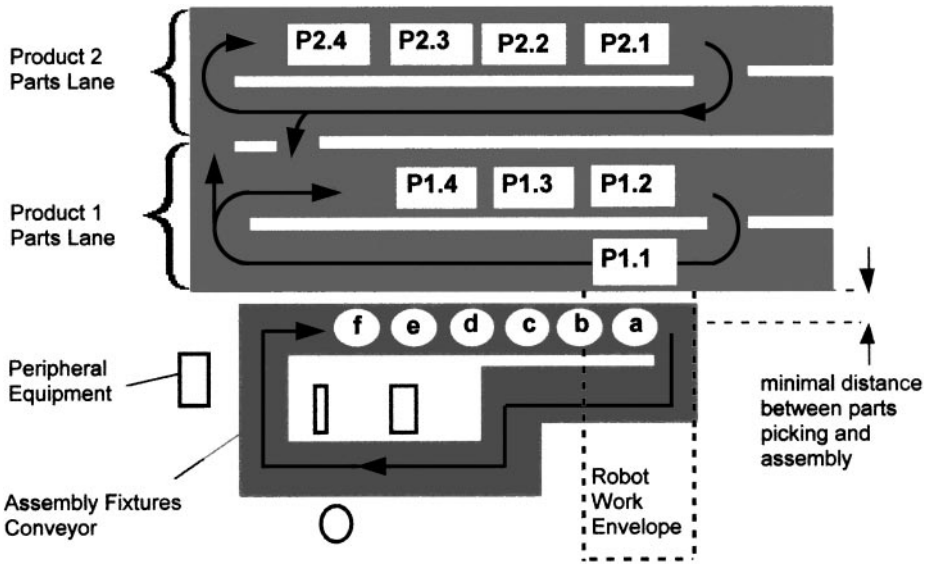


Fig. 2. The MARK II FAA cell and sub-batch principle

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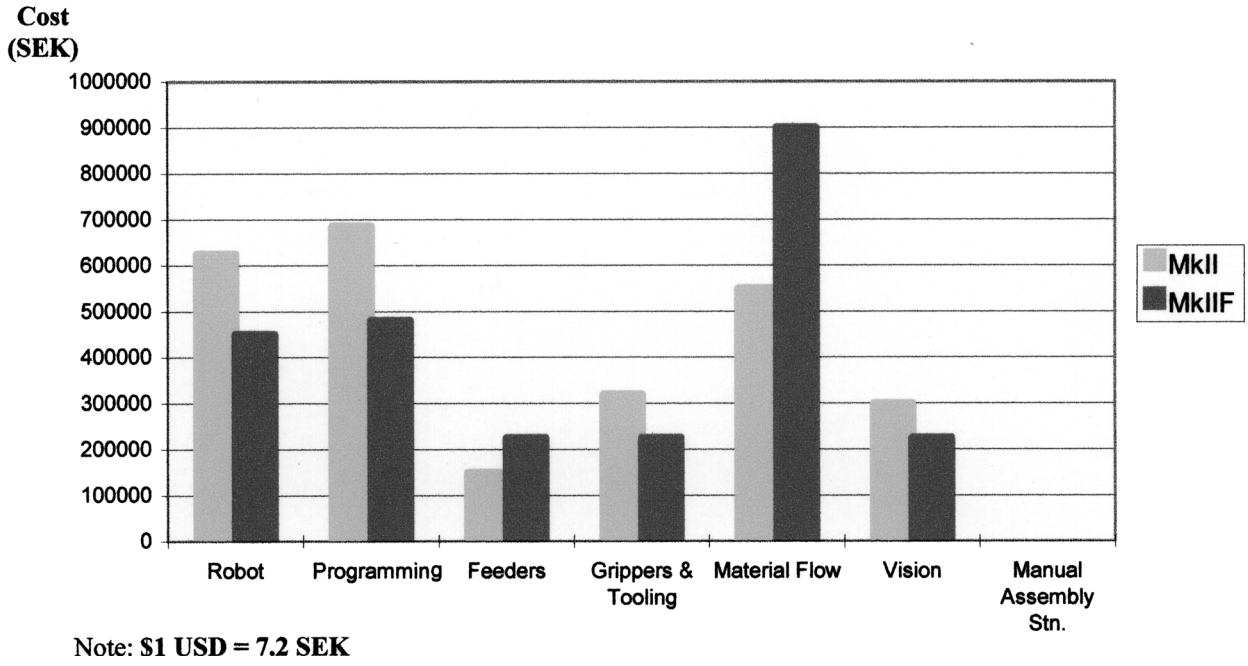


Fig. 3. The MARK II and MARK IIF FAA cell component costs

and flexible (some degree of adaptability), the process itself can neither be considered efficient nor easily controlled. Hence the need for a structured approach which combines the requirements of both programming and process control simultaneously.

3 REVISED FAA CELL REQUIREMENTS

The results obtained from our two previous installations led us to re-consider the driving requirements to be posed on a FAA cell. An important aspect is represented by what the relevant industrial needs for this technology really are. Our previous efforts did not meet all the requirements posed by industry, primarily because they were not clearly analysed from the outset.

3.1 Conventional operational requirements

The majority of products in Europe are not produced in high volumes ('hard automation' region): most products are produced in low-medium volumes ('manual' region). It becomes obvious that in terms of volume, one must concentrate on one-robot solutions in order to increase the use of FAA cells. To meet this goal, most companies assemble many different variants (or products) within an assembly cell. In order to further decrease the capital tied up in goods and lead-times, these variants/products tend to be asembled in small batches. Apart from automatic assembly of the products, the facts mentioned above create the basis for the standard requirements posed on a FAA cell:

- Automatic transport/feeding to/from the cell.
- Automatic set-up between batches.
- Automatic error detection and recovery
- High flexibility.

The two FAA cells designed by our research team, the MARK II and MARK IIF FAA cells, were both built and implemented along these requirements. These cells did not, however, meet all of the real industrial needs.

Other FAA cell solutions such as InFact,[10] DIAC[11] and MAX[12] have not found any major commercial success either, primarily due to the fact that they also denote the same drawbacks as the MARKII and MARKIIF cells. It is therefore important to clarify the reasons for which a modification of the original requirements is necessary.

3.2 Reasons for improvement

It was found that the requirement for 'high flexibility' is often applied in a shallow manner. The uncertainty regarding what to specify for a FAA cell is overwhelming for most companies. Consider that it entails that a period of at least 6-7 years must be forecast. The flexibility of our cells, as for most others, was therefore regarded not high enough!

The parts. Product parts which can be easily assembled manually may result in being difficult to assemble automatically. This is true even for products which have been explicitly designed for FAA.[13] This results in a delay in the automatic assembly of the product. It would therefore be advisable to design FAA cells with stepwise automisation capacities. Note that this reduces the risks and allows for the investments to be spread out over a longer period of time.

The Products. In order to increase the utilisation rate of the cell, as well as increasing the flexibility, a FAA cell should be capable of assembling a large range of products and product variants. This obviously decreases the capital tied up in goods for the user. This entails that the robot must access a very large number of parts. Ideally, a FAA cell must be able to account for large product/part; spans which vary in time and size.

Feeding Problems. The investment costs of a FAA cell depend heavily upon the number of assembled parts and their feeding solutions. Since they should account for a large range of products, the parts feeding creates constraints on

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floor space and direct costs. Therefore, an ideal FAA cell should allow for both simplicity and variety of feeding solutions. The ensuing large floor space should be easily accessed by the robot at all times.

Capacity. The problems linked to the capacity are, once again, based on the fact that it is difficult to foresee capacity increases several years in advance. One solution is to increase the utilisation of the FAA cell by running in several shifts. The next stage is not so apparent. Ideally, these increases in the production capacity should be achieved in a variety of ways, without disturbing the original layout.

Integrated Manufacturing. Past experience[7] shows that the need to integrate parts manufacturing into the assembly process is not negligible. Such integrations can reduce the feeding processes. This includes other non-manufacturing operations such as marking and packaging. This illustrates, once again, the need for large floor space.

Programming. The final requirement is a direct result of our own observations and is confirmed by most FAA cell users: the need for user-friendly and low-cost programming tools. Basically, the programming work in a FAA cell application must be rendered fast, simple and reliable. This also creates the need for FAA-tailored cell controllers. Furthermore, a programming and control system should not require special skills or training.

The industrial aspects detailed so far, combined to our previously described experiences, pushed us to formulate a set of operational characteristics for FAA cells. These characteristics have a direct influence on the programming and control aspects[14] (see below):

- Large Variant and Product flora it = Very large number of task programs.
- Short Lead-Times = Fast and reliable input of new programs.
- Short Product Life span = Programming time vs. production time is vital. operational control.
- Express Orders/JIT (0 change-over time)
- Stepwise Upgradeable FAA System = Steady input of new operations and equipment.
- Manual and Automatic Operations = User-friendly operator support and interface.

It is very obvious that a vast amount of finely-tuned (reliable) task programs must be generated often and with the lowest possible process downtime. The second observation is that a well formulated and strict management of these task programs is required in order to efficiently execute the varying production scenarios. Such aspects aid in clarifying the distinction between pure task programs and process control. Considering software maintenance and support fees, one must inevitably conclude that these requirements be fulfilled by a reliable and operator-friendly system.

All of the aspects mentioned above lead to the fact that such a programming and control system may inevitably result in an advanced software application which can only be programmed and run by experts. This must absolutely be avoided since new programming requirements can occur at short notice: short product life-cycles and constant inpout of new products/variants and operations. Other reasons include the fact that relying on external system engineers is expensive and can cause production delays.

3.3 The real industrial needs and FAA cell requirements

The industrial needs described earlier led us to add the following list of requirements[14] on a FAA cell

- enable stepwise automation.
- co-existence of manual and automatic operations.
- handle a large product/variant flora.
- allow for different feeding solutions.
- have a large capacity span (tenfold).
- integrate assembly and manufacturing operations.
- apply an easy to use, low-cost, programming and control platform.

4 THE MARK III FAA CELL

The MARK III FAA cell was designed and built along the requirements detailed above, and is currently operational. The MARK III FAA system is intended for small to medium sized products assembled in relatively low yearly volumes. Estimating a single robot operation's cycle time at 6 secs(average), it denotes a capacity of 1 million operations/shift and year.[15] This, together with short product life cycles and small batch assembly, represents the Swedish industrial needs.

The MARK III hybrid FAA system adopts a radical material flow approach: it uses a "reversed material flow". Instead of moving the parts to the robot, it allows the robot to move to the parts. This is accomplished by mounting the robot on rails (see Figure 4). The larger robot work envelope gives us the following advantages:

- one can introduce manual stations, thus enabling stepwise automatisation.
- practically unlimited floor space: parts can be fed in any way, large number of products/variants, integrated manufacturing stations, etc.. Note that the rail may be prolonged.
- the system capacity may be increased by installing another robot on the rail system.

The MARK III FAA system is hybrid in the sense that it can combine manual and automatic operations. It consists of a basic hardware layout we call the "standard machine",[16] and of product-specific equipment. The "standard machine" consists of (see Figure 4):

- a rail-mounted robot with fixture pallet and gripper tray.
- a wrist-mounted vision system.
- a pallet magazine and associated manual workstation.

The assembly is initiated when the robot moves to the pallet magazine and fetches a specific fixture pallet. The robot then moves to where the first part-type is to be picked. A gripper is mounted during rail motion (no time loss). According to the sub-batch principle, the robot then picks as many identical parts from the feeder as there are fixtures on the fixture pallet. When complete, the robot moves to the next part feeder/pallet. If a manual operation is encountered during the assembly sequence, the fixture pallet is shifted

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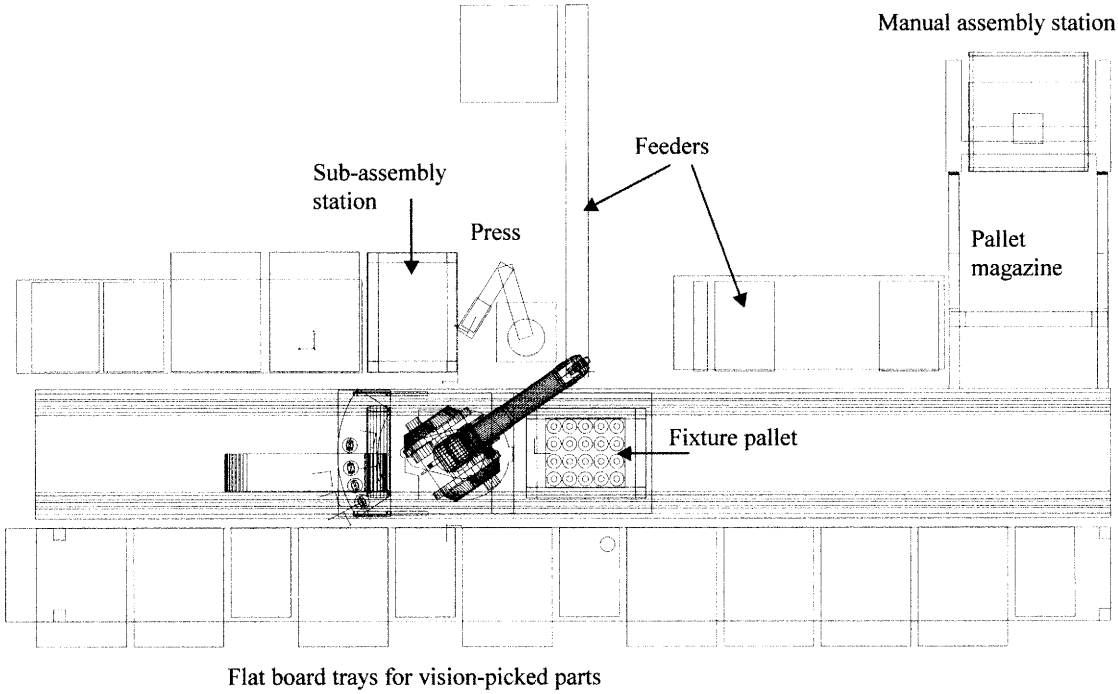


Fig. 4. The MARK III FAA system layout

out to the pallet magazine and the next product's fixture pallet is fetched. The robot, therefore, is never idle (Figure 5).

The pallet magazine acts as a buffer between the manual and automatic assembly processes. Several manual operations (fixture pallets) may be gathered so that the operator can assemble them at will. Depending on the product mix and number of fixture pallets, the operator's free-coupling time is between 30-90 mins.

The MARK III system can also account for sub-assemblies. These are assembled by the system and fed into the sub-assembly station along the rail. The system can, at a later stage, consider them as "parts". Furthermore, pressing operations are carried out by a passive "SCARA"-type device. Being mechanically guided by the robot itself, over the fixtures, it is a cheap way of handling press forces of 4000N.

The MARK III FAA cell is currently rigged for the assembly of high voltage outlets and plugs for ABB CEWE (since September 1994). Its current production details may be summed up as follows:

- Number of Products: 7
- Number of Variants: 40-200 standard, readily expandable to 800 customer specific variants.
- Annual Volumes: approx. 5/year-15000/year, depending on variant.

The assembled products are shipped back to ABB CEWE for marking and customer delivery.

4.1 The cell capacity

The MARK III cell capacity may be increased in several manners. The most conventional approach, increasing the number of shifts, is fully possible due to the fact that all cell programming tasks may be conducted off-line: there is

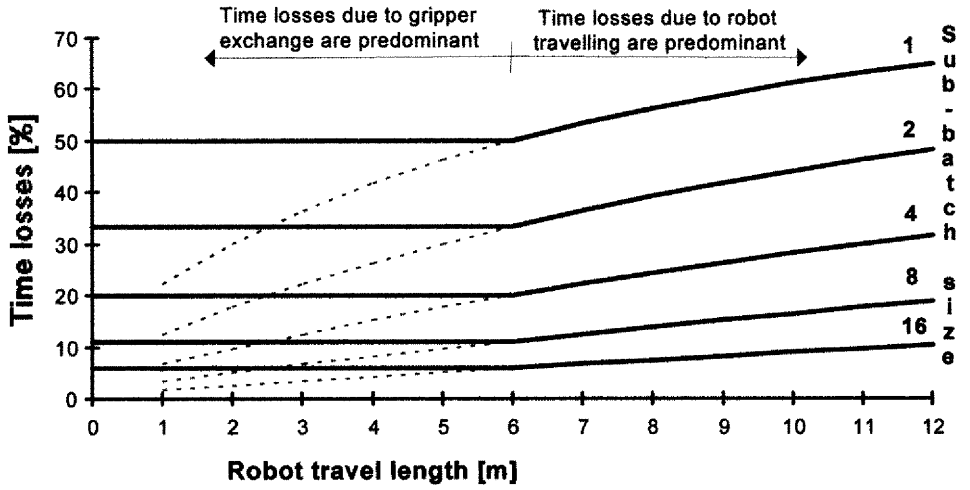


Fig. 5. Time loses due to robot travel

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practically no robot downtimes involved. Another approach is to identify and optimise time-intensive operations. A typical example is the picking and assembly of several identical parts: a more advanced feeding system may deliver all of these parts at once, thus eliminating time losses.

The most interesting approach, however, is to prolong the rails and, if need be, add another robot. This approach is fully realisable and has been confirmed by the robot manufacturer in question. Such a solution allows for major increases in capacity and also underlines the possibility to stepwise upgrade an existing FAA cell without disturbing the original layout.

4.2 Integrated manual and automatic operations

When the robot reaches a manual assembly operation, it feeds the fixture pallet out to the manual assembly station and continues working with another fixture pallet (another sub-batch). The new fixture pallet can be taken either from the outside (totally new) or from the manual station buffer (pallet magasine). The latter fixture pallet containing partially assembled products with completed manual assemblies. The cell controller ensures that the robot alternates between different fixture pallets (sub-batches) in order to maximise the system resources even during manual operations. The manual station buffer consists of an elevator device holding, in our case, up to five fixture pallets. With 20 fixtures on each pallet, this buffer allows for a disconnection between manual and automatic assembly of up to 1.5 hrs., depending on the amount of manual assembly/product. Hence the free coupling between the manual and automatic subsystems.

4.3 Stepwise automation

It is in fact possible to assemble products with one or more difficult components in such a cell since manual and automatic operations can co-exist without the traditional disadvantages for the operator (monotonous, stressing, etc.). The operations may be automated as soon as an economical/technical solution has been found to the problem. The new equipment can be placed along the rail and tested. Manual operation can resume whenever the operation needs trimming. This enables system investment decisions to be taken in a stepwise manner, hopefully giving a boost the degree of assembly automation in industry.

5 THE FACE SYSTEM

One of the most important aspects regarding the development of the FACE system was the functional perspective of the automatic assembly process. Commonly, FAA cells are designed and implemented for a known range of products and hence deploy a given layout and strategy. These cells usually denoted problems in terms of long-term flexibility. This is of particular relevance since most cell controllers are built upon the general operational aspects of FAA cell processes. Our research pointed out that the FAA cell processes could not alone provide a generic framework onto which one could model, or build, the control code. It was therefore decided to revert the attention upon the workpieces themselves: the products. Relevant parameters are specified at a *supeiror* level. The assembly-ready products arrive at the cell with information regarding the assembly method, order ID, delivery date, the parts, associated feeders, etc. The FACE system is founded on the idea that the assembly process in its most *general* form creates the basic operational constraints. Such constraints may, in turn, be used to structure the information contained within the products.

5.1 The concept

The mainframe of the FACE systems's control code was developed from a commercially available relational database system (Microsoft ACCESS™). This is a SQL, ANSI-standard relational database system. The main reason being the far more powerful data manipulation capacity such systems have over more conventional database systems, as well as the improved data exchange.[17] Working along client-server principles, they allow for data independence (decentralised database).

The efficient use of relational database techniques (Figure 6) presupposes, or demands that, the information is structured appropriately. The FAA cell process aspects are exploited in order to structure the information. As an example, consider the following (typical) FAA cell process demands:

- order number and delivery date must be given.
- the order size must be given in order for the batch/sub-batch size to be calculated.
- the product must be subdivided into parts.
- the assembly sequence should be given (specified at a higher level).
- parts-related information should be given (delivery station/feeder, associated assembly fixture, etc.).
- the assembly method must be given (manual, automatic, or mixed).

The above example depicts a typical sequence of demands posed by an order-driven assembly process. The demands are *not* limited to automatic assembly, and are therefore general to *any* assembly process. Basically, the driving process parameters are being used as a framework for the extraction of information from the assembly-ready products. The information can easily be stored in database "tables", whilst the framework stipulates what is stored where, how and in terms of which relations. This results in a structured approach to the definition of the relational database and related code.

The data retrieval is carried out by the queries, which can either retrieve the data "on-the-fly"(snapshot) or by activating a dynamic search (dynaset). The latter searches for particular information and will inform the control code when the given status is attained, with relative data. The data tables may be readily updated by the user or by the control code.

Due to the de-centralised database and secure data handling, most of the updating and input of new orders can be carried out off-line. Since the relational database works according to client-server principles, it allows for the robot

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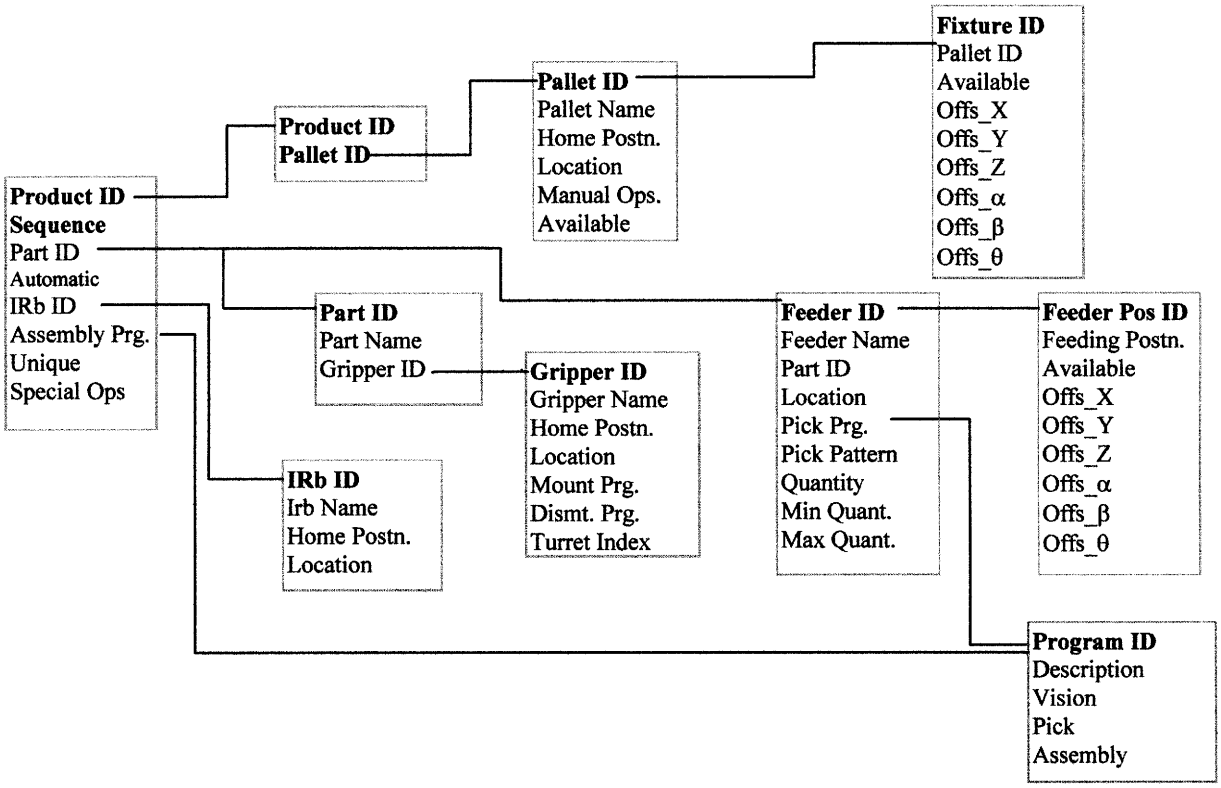


Fig. 6. Data tables and relations associated to the detailed scheduling and dispatching[17]

programming and data input functions to be accounted for by other software modules.

5.2 The FACE architecture

The main functions which the FACE system is designed to account for are cell control, process supervision, and robot task program generation. Due to the de-centralised database and networking possibilities, it was decided to develop a separate module for each of these functions. This led to the development of the following three software modules:

- Control Module
- Supervision Module
- Robot Motion Module

Only the Control Module is compulsory for the running of the FAA cell. The FACE system architecture has been implemented mainly according to the revised PAC model.[18] The major differences relate to the fact that FACE addresses the programming aspects as well (Figure 7).

Note that FACE operates at cell level. It does, however, allow access to any area or factory controller with

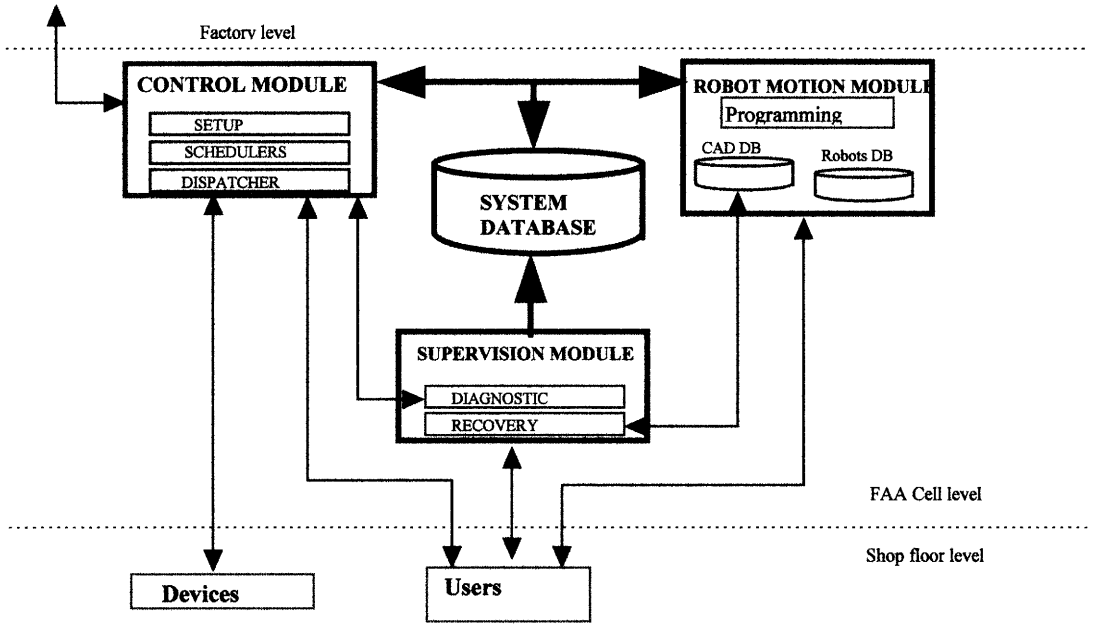


Fig. 7. The F.A.C.E. system architecture

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acknowledged priority. A short description of the Control and Supervision Modules will follow.

5.3 The control module

All FAA cell management and control operations are executed from the Control Module. The Control Module is built upon different internal operational blocks (control processes), each of which is responsible for specific functions.

These operational sub-modules cannot exchange operational functionality, but may access, manipulate and write to the same data tables. The Control Module functions may be summed up as follows.[17]

- process data handling (relational database).
- scheduling of events.
- generation of assembly sequences.
- dispatching of tasks.

Note that the relational database must be considered part of the Control Module if the FACE system is implemented in its basic configuration. It has therefore been developed concurrently to the control code residing within the Control Module.

The Schedulers. The FACE Control Module operates with two schedulers: the short rane and detailed schedulers. The subdivision is due to the periodicity and horizons involved with the tasks they are to handle. The main task of the relational database (in terms of the control functions) is the handling of data input to the system. Although data may be input in different ways, the FACE system allows this via the Supervision Module. The type of data received by the relational database is as follows:

- customer order (Order ID)
- which product (Product ID)
- the quantity
- the duedate
- customer ID(optional)

This information is exploited by the short range scheduler which triggers a search for further information regarding the ability to perform an assembly of the given product. If the search concludes that all the necessary information is available it will term the product order as "Ready-ForAssembly".

The sort-range scheduler also derives the required number of product specific sub-batches according to the amount of fixture pallets available. The short-range scheduler can handle any size of sub-batch.

The next stage involves the detailed scheduler, which is event-driven and dynamic. This scheduler searches through specific tables and relations for part and fixture pallet availability. Its main task is to produce operation lists, which consist of series of NIOs: non-interuptable operations. Being dynamic, the detailed scheduler is capable of deriving a new list of NIOs in case certain events occur. Such events may include the input of new orders (even "express orders"), acknowledged completion of sub-assemblies, lack of parts, etc.

The Dispatcher. The dispatcher is concerned with real-time operations. The operations carried out by the dispatcher may not influence the assembly process cycle time. Its main task is to distribute the tasks given in the NIO list to the respective resources, according to the assembly cell status. It is important to note that, for the dispatcher, the data transmission speeds (communications) are just as vital as the processing speed. A major feature in the development of the dispatcher was the strive to decentralise the task handling and execution requirements. The resulting minimisation of data transfer required also enables an easier application of the tasks into parallel processes. The dispatcher also logs all the executed events to the relational database. This is done by having the NIO return a result code to the database. The operator has therefore access to a list of executed operations which is readily available whenever a failure may occur. Note that the relational database also holds a record of the FAA cell's production status, ongoing orders and sensor data (Figure 8).

5.4 Supervision module

The main function of the Supervision Module is to assist the operator in the daily management of the FAA cell control

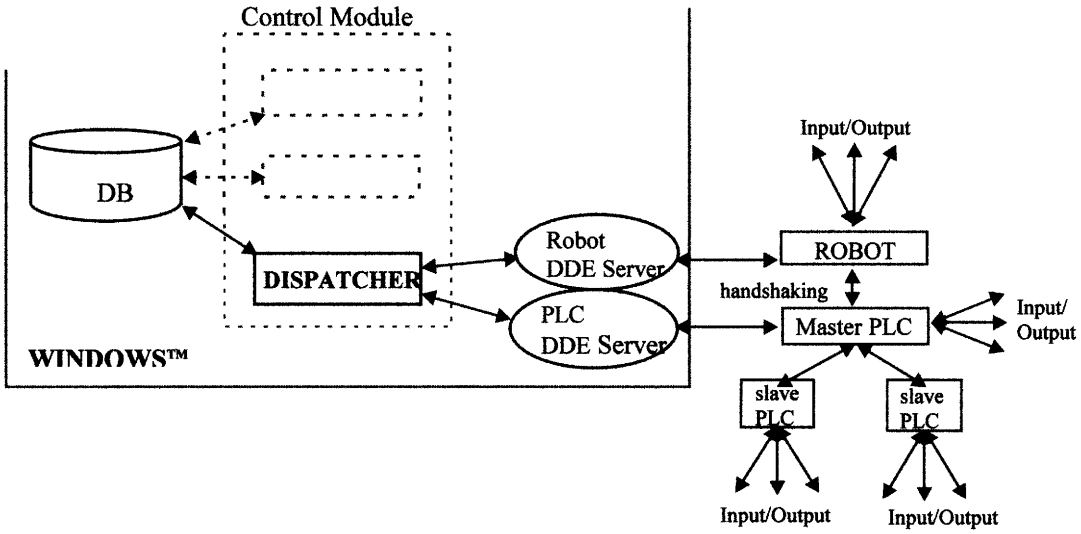


Fig. 8. The dispatcher control structure[17]

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requirements. Its secondary function, which is still under development, is to perform error detection and recovery functions. This work was initially investigated by D. du Bellay[19] and is currently being developed into a more concrete solution by M. Shibuya.[20]

At present, it is an advanced MMI to the FACE control module. It consists of a series of active windows through which the operator can input information and receive work status data. Typical examples are:

- new order data.
- new parts balance after feeder/tray refill.
- equipment re-configuration data (i.e.- non-permanently rigged product variant).
- acknowledged completion of manual assembly.

The operator also receives data about the process and related work demands. This is done via interactive displays such as shown in figure, and contains the following information:

- current robot position.
- current part status in feeders/trays (overgoes to red if critical).
- current order and sub-batch being assembled.
- available de-coupling time for operator (estimated).
- next order/fixture pallet assembly.
- current manual assembly demands.
- call for missing data relative to a given order.

This information allows the operator to organise his/her job type and schedule accordingly. The operator can therefore assume responsibility over his/her own de-coupling time from the FAA cell. The Supervision Module is developed in Microsot Visual Basic™ thus enabling a problem-free access to the relational database (Microsoft ACCESS™). The communication is ensured via a standard TCP/IP network.

5.5 The robot motion module

The Robot Motion Module (Figure 9) is the second optional module within the FACE architecture and is used for the off-line generation of robot task programs and associated simulation/validation work. This module has been developed from a commercially available CAR system into a PC-based, task-oriented platform for FAA cells. It is designed for use with cell controllers and not robot controllers. Since the Control Module has command of the assembly system functions, orders and parameters, the resulting demand on robot motion programs is very task-oriented. Several, small robot task programs are requested and administered by the Control Module. These robot task programs are very specific in nature. This is a very important aspect since it defines a set of standard robot task program types.

The first step was to remove all unnecessary functions from a commercial CAR system, leaving only those necessary for FAA system program generation and cycle time simulations. Secondly, *macros* which call the necessary functions to create specific task programs were created and embedded within the CAR system.



Fig. 9. The robot motion module

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These programming macros represent the programming menu for the operator: the Task Planner - see fig. 9. Hence there is no need for any special skills. When the operator chooses one of these program generation macros, the system will demand for specific inputs. These appear in pop-up menus (list of defined choices).

Finally, in order to create reliable robot programs, calibration functions were added. The Robot Motion Module includes model calibration functions as well as cell calibration functions.[21] The cell calibration is carried out with the aid of a force/torque sensor. Note that the object-oriented software stores all programmed poses in terms of objects. When re-calibrating a reference object, one also adapts the old programs to the new situation. One therefore obtains program adaptability and a reduction of the re-programming needs.

6 RESULTS

The MARK III FAA cell has fulfilled all of the initial requirements. It is stepwise upgradeable, it accounts for a very large product/variant flora, and has successfully integrated automatic and manual operations. The latter aspect was tested by two experienced industrial manual operators over a two week period with full approval. In terms of costs (Figure 10), the MARK III cell has performed better than its predecessors in many ways.

Although it accounts for a far greater product span than its predecessors, the MARK III cell denotes great cost reductions in programming, grippers and tooling, and material flow costs. Obviously, the fact that the robot moves on a rail creates slightly higher robot costs. However, these costs are lower than the gains obtained in terms of material flow costs: no parts and/or fixture conveyors are required.

Note also that the much larger product and variant span did not create a proportional increase in costs for the feeders. The interesting aspect is that the MARK III cell has been very successful at reducing the *recurrent* cell component costs: component costs incurred when introducing new products or variants. That is to say that programming, feeders, grippers and tooling costs are not directly affected by how many products or variants the cell is to assemble. This is of some importance since it does increase the economical flexibility of the FAA cell: consider the function given below.

$$\text{economical flexibility} = f\left\{\frac{\text{fixed costs}}{\text{recurrent costs}}\right\}$$

If one assumes that the economical flexibility of a FAA cell is a function of the fixed costs divided by the recurrent costs, one *must* strive to cut back on the latter costs.

The MARK III concept also proves to minimise the risk factors considerably. The time taken to input a completely new product (all variants) into the cell is of *two* days. This includes finely tuned robot task programs, grippers, and so forth. Conventionally, this procedure is usually a matter of *months*! Programming and control risks are therefore eliminated with the FACE solution. Feeder risks are also eliminated since the cell allows for any type of feeder solution, and, should a solution create problems, the operation may be manually executed (without loss of production) until the problem is solved.

The MARK III cell for the named production scenario cost approximately $690,000:-USD. Note that these costs are related to the particular robot type used: the application required a 6 d.o.f. robot. The MARK III concept may be applied to a cheaper robot type (SCARA)! This sum can be subdivided as follows:

Standard Assembly Machine	=$350,000:-USD
Product-Specific costs	=$340,000:-USD

The basic system, or “standard assembly machine”,[16] consists of the robot, rail motion, vision system, manual assembly station and FACE control module. The product-specific costs are created by the feeders, grippers, fixtures, and installation. The costs are therefore not yet as low as one would like them to be, but there are some important considerations. These will be detailed in the following section.

The pilot MARK III cell can be further developed to create a standard assembly cell—the MARK III Assembly Machine. By standardisation the cell costs for the basic

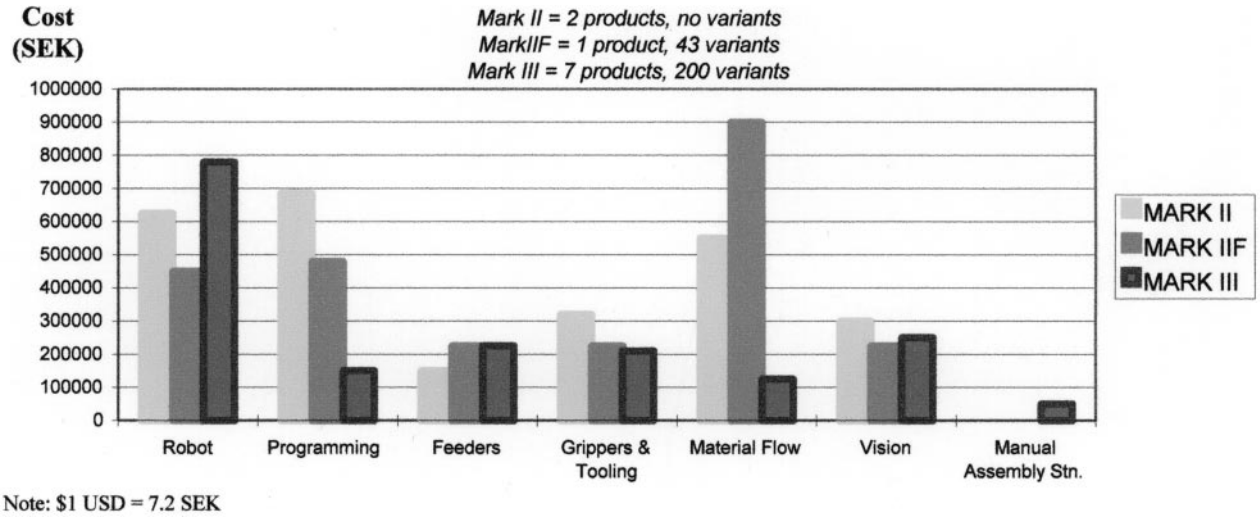


Fig. 10. Comparative cell component costs

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system could decrease making it possible to induce more installations. Many cells would result in a series-effect, further reducing the costs. This is not a new concept since the SONY SMART and Super SMART Cells may be considered as an example.[22] The MARK III cell places FAA cells at about the same evolutionary stage as NC-machines were 20 years ago: it is now possible to purchase standard assembly machines. The specific tooling such as feeders obviously remains quite expensive. New flexible feeders such as the modularized examples given by the FAMOS FLEXFEED project[23] will soon provide cheaper feeders, especially for FAA cells.

The MARK III cell is truly flexible and offers a low risk potential: there will be no surprise delays in the production start and the added costs for the introduction of new products/variants are definitely minimised (Figure 11).

Programming & control cost aspects, which are so often avoided when considering installation costs, have been radically improved. Note that the MARK III cell is fully productive in a matter of days in contrast to 3–4 months for the SMART cell.[24]

The FACE programming and control system has radically changed the potential of FAA cells. Not only have the programming costs been reduced, but new opportunities have been made available: combined manual and automatic assembly, unpredictable (express) order schemes, continuous update of operations/equipment/orders, vast variant floras, and so forth. All of the benefits have been achieved by a system which does not require frequent external support, extensive training[21] nor high purchase costs. FACE is a low-cost, PC-based, modular solution which may be expanded at will to include fully integrated cycle-time and discrete event simulations and FAA-tailored off-line programming (task-oriented[21]).

7 CONCLUSIONS

The decision makers within most companies often determine the viability of a FAA cell in terms of its playback period or capacity to generate return on investment. In practice, what renders a FAA cell viable is its capacity to absorb work and strategic changes at a minimal cost, over a sufficiently long time-span, all whilst maintaining a high quality output. It is therefore difficult to predict how viable any given cell might be, and one of the main reasons for this has been the inability to perceive the impact that programming and control actually has on a FAA cell's efficiency. As detailed, the development and application of the FACE system allowed the MARK III cell to minimise the impact of programming on the overall costs. The MARK III application therefore meets the original objective of applying an easy to use, low-cost, programming and control platform. The MARK III cell assembles about four times as many products and hundred times as many variants as its predecessor the MARK II FAA cell did. The astonishing fact is that the programming costs incurred by the MARK III cell are over five times *less* than those incurred by the MARK II cell!

The second source of problems resides in that most failures are accountable to the lack of flexibility and/or adaptability of such cells, words which themselves give rise to a myriad of different definitions. What such terms do point out in a certain manner is that specific costs and related risk factors have not been particularly well analysed. The application of the reversed material flow, coupled to the sub-batch principle, allows the MARKIII cell to meet the remaining objectives (see section 3.3). This cell is stepwise upgradeable and allows for the co-existence of manual and automatic operations. Coupled to the new software, the MARK III cell is able to assemble over 200 variants of 7 products and is readily expandable to four times as many variants. It therefore meets the objective of handling a large product/variant flora. Its mechanical configuration and material flow principles also allow for the adoption of almost any feeding solution (see figs. 4, 6). Examples are also given as to how the capacity may be increased without incurring major changes in the cell layout (see section 4.1). The MARKIII FAA cell has therefore met all of the project objectives.

This FAA cell has been operational since 1994 without incurring any major problems. Feasability studies are being carried out for a number of Swedish companies.

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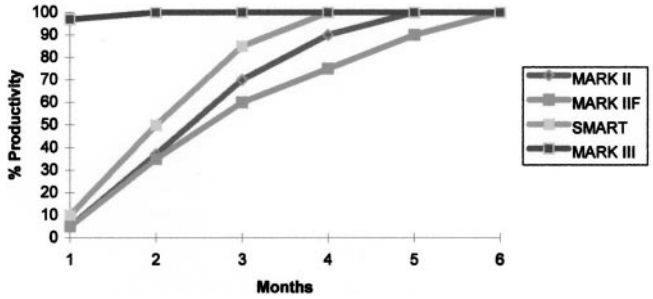


Fig. 11. Time taken to attain full production levels

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