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Managing Iterations in Product Design and Development

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***Abstract*—**The inherent iterative nature of product design and development poses significant challenge to reduce the product design and development time (PD). In order to shorten the time to market, organizations have adopted concurrent development where multiple specialized tasks and design activities are carried out in parallel. Iterative nature of work coupled with the overlap of activities can result in unpredictable time to completion and significant rework. Many of the products have missed the time to market window due to unanticipated or rather unplanned iteration and rework. The iterative and often overlapped processes introduce greater amounts of ambiguity in design and development, where the traditional methods and tools of project management provide less value.

In this context, identifying critical metrics to understand the iteration probability is an open research area where significant contribution can be made given that iteration has been the key driver of cost and schedule risk in PD projects. Two important questions that the proposed study attempts to address are:

Can we predict and identify the number of iterations in a product development flow?

Can we provide managerial insights for a better control over iteration?

The proposal introduces the concept of decision points and using this concept intends to develop metrics that can provide managerial insights into iteration predictability. By characterizing the product development flow as a network of decision points, the proposed research intends to delve further into iteration probability and attempts to provide more clarity.

***Keywords*—**Decision Points, Iteration, Product Design, Rework.

I. Introduction to Iteration

ITERATION is the process of repeating tasks within a design project, and is common to all types of engineering design. Iteration is primarily re-work and repetition of the tasks in product design and development (PD). In many ways, PD is a creative, discovery process [19]. While product design quality improves with successive iterations [24], [25], [27], [31], iteration is a key driver of cost and schedule risk in PD projects [3], [5], [16], [29].

Osborne 1993 [17] found that the nominal flow and expected iterations accounted for between 30% and 87% of the overall time (mean=70%, =17%). Unanticipated iterations for these projects accounted for the remaining 13% to 70% of the lead time (mean=30%, =17%). The iterative nature of design and development is well illustrated as spiral development process (using software development as an example) [4].

Browning et al. 2002 [7] state that "instead of doing exactly the same thing over and over, PD seeks to create a design that has not existed before". Product design and development many times works on creating new design that has not existed before. Due to the newness of the designs, the designers and the organizations learn as the development happens. Identification of what will work and what will not work happens as the design evolves with multiple iterations carried out before the expected specifications are met. Terms like "iterative" and "creative" apply to PD.

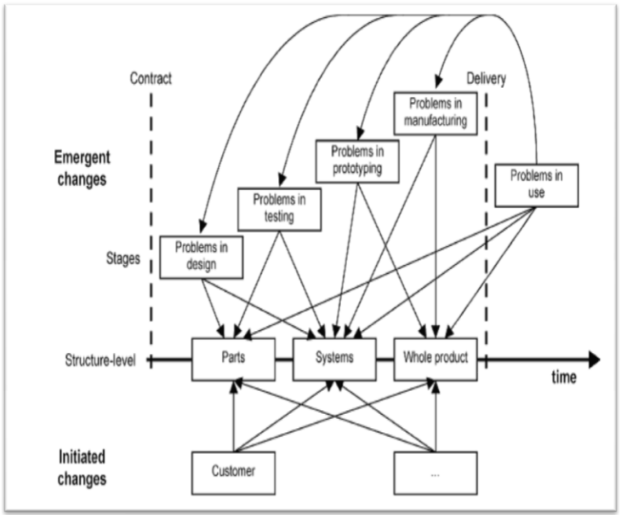

Fig. 1 Iterations due to problems in use, design

The Fig. 1 [12] shows the possible iterations in a product development. The iterations or re-work can originate from problems in use, problems in prototyping, problems in testing and problems in design.

A. Types of Iteration

Robert P. Smith et al. 1997 [22] examines the reasons for design iteration and describes models of design iteration. In studies of iteration in industrial practice, Robert P. Smith et al. 1997 [22] have documented various forms of iteration and show that the iteration is typically necessary for two reasons: an unexpected failure of a design or prototype to meet established criteria and an expected response to information which was generated after the previous iteration was completed. Both types of iteration are typical of most engineering projects. Robert P. Smith et al. 1997 [22] identified 2 forms of iterations.

- First is the time it takes a team to create the nominal design. This includes the first-pass design and anticipated iteration in the internal design process of each team.
- Second is the unanticipated iteration including rework due to internal errors, errors by other groups, and changes in product strategy.

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Iterative rework taxonomy introduced by Richard et al. 2005 [21] provides further classification – evolutionary, avoidable retrospective and avoidable corrective types of rework. Richard et al. 2005 [21] classified the type of rework into evolutionary, avoidable retrospective and avoidable corrective. The evolutionary rework typically occurs when the developers could not have known about or foreseen the changes that happen in user requirements, market requirement and design constraints. Retrospective rework occurs because developers knew the needs but did not accommodate them for reasons such as lack of time, time to market pressure. Avoidable rework is primarily the rework involved in fixing defects due to incomplete development.

Ulrich and Eppinger 2000 [30] define iteration as repeating an already completed task to incorporate new information. Iterations are inherent in design and development since it is many a times a heuristic reasoning process. Adams and Atman 1999 [1] provide an information centric view that involves gathering information, processing, identifying possible design revisions, and executing those revisions in pursuit of a goal. Adams and Atman, 2000 [2] also define diagnostic iterations to differentiate between iterations that involve evaluation of design tasks as compared to transformative iterations that synthesize new information. In many situations coupled tasks and information dependencies create feedback paths between tasks and result in iteration and rework. Smith and Eppinger 1997 [26] discuss about sequential versus parallel iterations. Denker et al. 2001 [11] outline interdependent task cycles.

It is important to differentiate between exploration, convergence and rework as all of them are iterative in nature. David Wynn et al. 2005 [10] have provided a definition that can be used to differentiate these. Ramon Costa et al. 2003 [20] have classified the iterations into three broad categories as re-work, design and behavioral. The classification is based on identifying the changes in the abstraction level of the design and the scope of the design. The iteration type is classified as rework if there is no change in abstraction level or in the scope. This type of iteration is seen when there are errors in the completed tasks. Design iteration may involve with the activity's abstraction level being not the same as in the first execution. The third classification is Behavioral iteration. The behavioral iteration involves repeating the tasks at the same abstraction level but on a different sub-problem. The design decisions involve many times division of the high level design into multiple smaller sub-problems. The task is repeated through each of the sub-problem to provide a final solution. In this scenario the abstraction level is not changed but only the scope changes.

B. Decisions - Importance of Information and Decision Making

The product design and development can be viewed as a collection of decisions and the iteration can be understood as either change in the decisions or re-work due to wrong decisions. Few interesting references in the literature can be found regarding the viewing of product development as a decision production system. Jeffrey W. Herrmann et al. 2002 [15] comment that the product development is an information flow governed by decision-makers who make both design decisions and development decisions under time and budget constraints. In this information flow process a decision-maker gets some information, makes a decision, and consequently generates new information. Part of the "makes a decision" step may involve sending and receiving information from others. Decision-making requires information, generating information, and determining who gets which information. A product development organization is described as a network of people using information, making decisions, and generating information [15]. Design involves the desire to create useful information, which is acted upon by a number of activities and disciplines [15]. Browning 2002 [6] state that "the information is valuable if it decreases the risk that the product will be something other than what it is supposed to be—i.e., if it improves confidence in the recipe. Trying, analyzing, evaluating, testing, experimenting, demonstrating, verifying, and validating can create valuable information. The information creation process is indeed a sequence of events and it is important to make sure the interdependencies are factored in this information creation, decision making process. Certain information must be created and propositions made before it becomes possible to create other information". For example, components must be designed to some level of detail before certain kinds of information is available about assemblies of those components. The dependencies between PD activities define a necessary sequence in the process of producing useful information ([8], [9], [16], [18], [23]). Most of the work done and the decisions made depend on the results of other's work and decisions—i.e., on the structure of the activity network [13]. The value of the information an activity produces is a function of, among other things, the value of the information it receives and uses. In general, then, activities are done to create deliverables, and the value of an activity depends on the value of the deliverables it uses and creates [7].

Fundamentally a product development organization is a network of individuals who process information and make decisions under time and budget constraints. Jeffrey W. Herrmann 2002 [15] describes such organizations as decision production systems. Such a view provides needed focus on information processing and decision-making flows instead of personnel reporting relationships and help organization members understand the flows of information and decisions in the same way that an organization chart describes administrative authority relationships and a process plan (routing) describes the flow of material through a factory. These aspects are articulated by Jeffrey W. Herrmann 2002 [15].

The Giovanni D'Avino et al. [14] proposed parameter-based model of design process based on an understanding of the design process as a series of decisions on parameter values. An interesting approach of using the decisions as a control valve for information flow is discussed by Sule Tash Pektas et al. 2006 [28]. Sule Tash Pektas et al. 2006 [28] state that the state of the system is brought to the desired level by operating a valve (a decision point) that controls the information flow toward the state of the system. Information is translated into actions in the decision-making point, according to the decision-making policies, thus modifying the state of the system [14].

II. Strategy to Manage Design Iteration - Introduction to Decision Points

Entire product development involves many decisions and each decision can either make an improvement towards the final product or can be a step back due to it resulting in re-work and re-design. The decisions determine whether the progress has been made towards achieving the goals or there is a need to rework or iterate the earlier completed work items. Extending the decision point concept to product development flow and using this concept to identify iteration probability is a novel idea introduced by the authors. Planned decision points are for example reviews, testing, early prototyping etc. Pre-planned decision points indicate the existence of planning for iteration in a product development or possible events in the development flow when iteration may occur. Authors in this paper view the entire product development as a network of decision points and provide insight into identifying the iteration probability of the product development flow.

Decision points are typically an event in the product development flow where a decision is made. If the decision is not favorable – then the impacted work-items are reworked or iterated. For instances (Fig. 2) the tasks T1, T2 and T3 (specification), T4 (customer inputs) provide inputs to a decision point D whose decision will indicate if we have to rework. There are several structures of decision points one is likely to encounter in a product development flow.

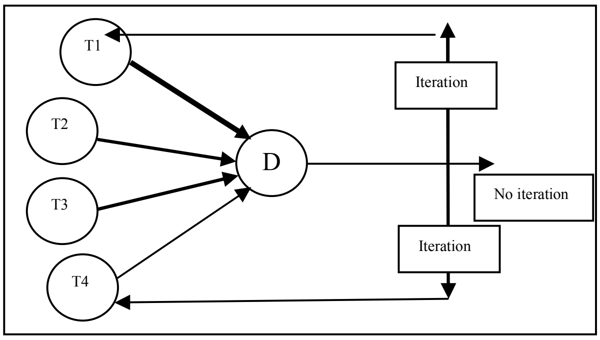


Fig. 2 Simple decision point visualization

A. Extending the Simple Structure

One can extend the simple structure to include 2 TO N Tasks combine to produce a decision. In this scenario, the decision can be determined only when all the inputs are available. For example, in many products, the final product performance can be measured only when all the sub-components are integrated together. Such a decision point would be an N to 1 decision point. The decision point may also generate one or many results. The N to M decision point has N inputs and M outputs while the N to 1 decision point has N inputs and 1 output.

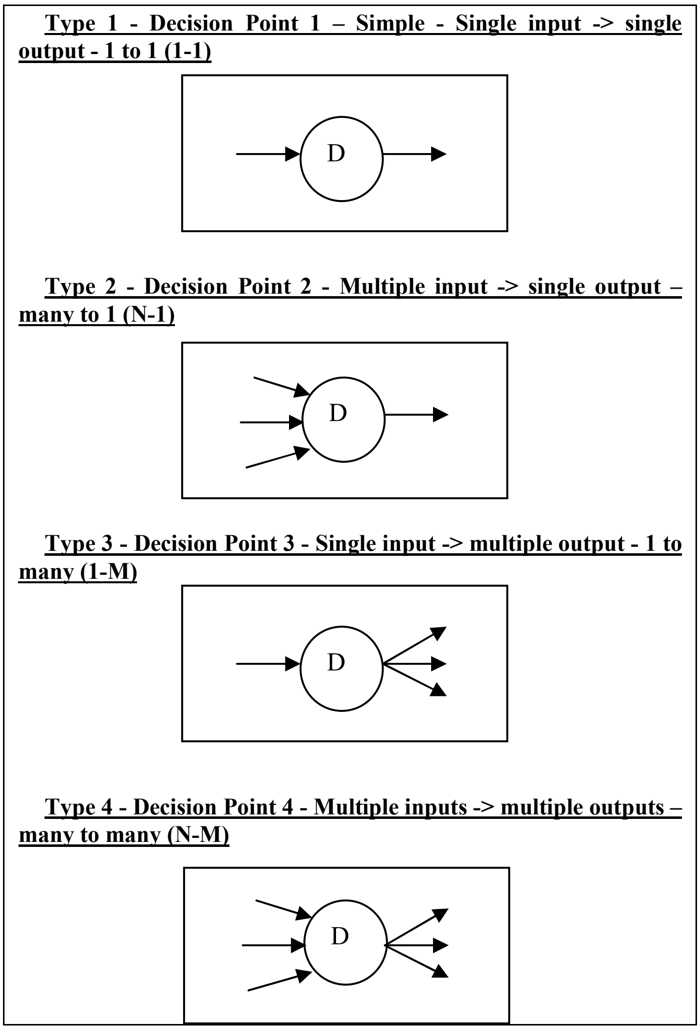


Fig. 3 Types of Decision Points – Based on Number of inputs and outputs

III. Three Dimensions of Decision Points

Each decision point takes in several inputs for the decision making, uses certain criterion to decide on the output decisions. The decision points can be categorized by using the volume of inputs and outputs (quantity of information used for processing and number of decisions to be made) and the expertise involved in decision making.

A. Volume of a Decision Point - Quantity

Volume of a decision point can be defined as the quantity of information processed (inputs) to decide the outcomes. It also includes the total number of decisions that are made (output). The volume can be determined by identifying the

- Number of inputs to a decision point – we can classify as 1 input, 2 inputs … N inputs
- Number of outputs of a decision point – how many outputs we generate 1 output, 2 output ….. M outputs

Based on the input and outputs the decision points can be categorized as 1-1, 1-M, N-1 and N-M decision points (refer to Fig. 3).

B. Expertise Involved in Decision Making

Expertise involved in a decision point is the level of human involvement vs. machine involvement in the decision making. This can be identified by identifying the level of hard and soft information used for making decisions. Hard information is information that is more quantifiable while soft information is expertise, experience based information (the quantity of hard information (relative to soft information) increases as the knowledge about the product increases). "Some of the information used in arriving at a decision may be hard, that is, based on scientific principles and some information may be soft, that is, based in the designer's judgment and experience."

Expertise can be determined by identifying the number of people involved in decision making and the number of people involved in reviewing the decision. Important factors to identify the soft vs. hard information or the expertise involved in a decision points are

- Number of decision makers
- Number of decision reviewers
- Usage of results from prototyping, simulation
- Ability in analyzing the results using machines

C. Information Quality

When the decision points are interconnected, the decision making process gets influenced by the way they are sequenced and planned. Primarily the input information quality will be impacted by the nature of planning. For instance in an overlap and concurrent development flow the decision points may have to work with incomplete information due to overlapping or concurrency of tasks in the development flow.

Due to overlap – concurrency of tasks - decision points may have to deal with information that is incomplete and partial (resulting from tasks and work items that are not 100% complete).

Due to inputs coming from other decision points in the network - the interdependency on other decision points impacts the decision making. Primarily the decision point may be re-visited multiple times due to changes in decisions or input information feeding into the decision point.

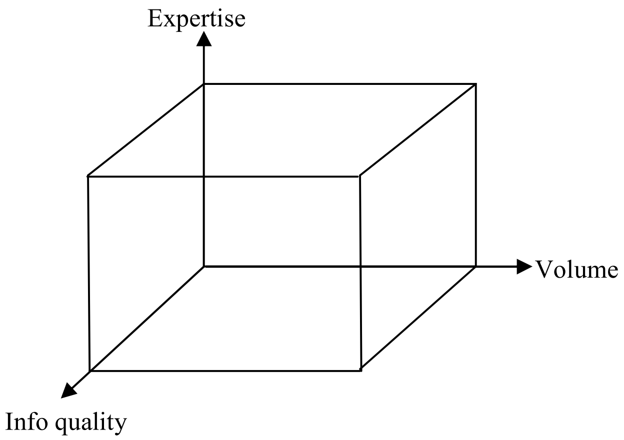


Fig. 4 3 Dimensions of a decision point

IV. Study of Iteration using the Three Dimensions of Decision Points

Decision points are the primary sources of re-work and iteration in a product design and development. The three dimensions of the decision points can be used to identify the relationship between them and the iteration.

Volume – Higher the quantity of information that needs to be processed at the decision points higher will be the probability of revisiting the decision point. The volume of information is an indirect indication of the complexity involved in the decision point. Higher the complexity higher is the likely-hood of the decision being later revisited for errors.

Expertise – The expertise involved in the decision making indicates the vulnerability of the decision point to changes. Higher the involvement of human expertise – higher the probability of iteration due to errors and incorrect decision making. The involvement of human expertise is a clear indicator of complexity involved in the decision making.

Information Quality – information quality impacts the decision making as any errors or change in input information will result in a revisit of the decision point leading to rework and iteration. The information quality is primarily dependent on the level of overlap or concurrency and the connectivity with other decision points in the network. Higher the overlap or concurrency – decision points have to work with more incomplete information. Greater the information coming through these decision points – greater is the vulnerability to iteration and re-work.

By studying the three dimensions of a decision point one can identify the iteration probability of a decision point. The authors further extend this to a network of a decision points representing a product development flow.

V. Iteration - Viewing Product Development as Collection of Decision Points

Decision points are dispersed across several stages of a product development flow. By studying the decision points and characterizing the volume, expertise and information quality at each decision point, the iteration probability of a decision point can be determined. Similarly the network of decision points can be extended to study the iteration probability of the entire network. Authors are proposing a novel framework using the three dimensions and the network of decision points.

- Each decision point can be associated with a risk or probability to revisit based on the volume, expertise and information quality.
- Viewing the entire product development flow as a collection or network of decision points can help to identify vulnerability of the development flow to re-work and iteration
- One can then explore the iteration probability of the product development by analyzing the distribution of the decision points and the structure of the decision point network

Authors propose following metrics using the concept of decision points and its dimensions. Proposed metrics below can be used to identify the probability of iteration.

1) Metric 1 – Density of Decision Points

The decision points will be generally spread across the different stages of the product development (specification, low level design, high level design, implementation, testing etc). Study of the density of the decision points across the different stages will provide a measure of iteration probability. This is illustrated through 4 examples.

Example - Density of the Decision Points Concept

4 different examples for 4 different patterns of decision point's distribution are given below in Table I.

TABLE I
4 EXAMPLES WITH VARYING DECISION POINT DENSITY IN A PRODUCT DEVELOPMENT FLOW

Stages	Number of decision points Example 1	Number of decision points Example 2	Number of decision points Example 3	Number of decision points Example 4
1	10	27	24	23
2	12	23	16	21
3	14	19	13	22
4	15	18	26	18
5	15	16	20	20
6	16	15	19	19
7	18	15	17	22
8	19	14	27	23
9	23	12	18	21
10	27	10	15	22

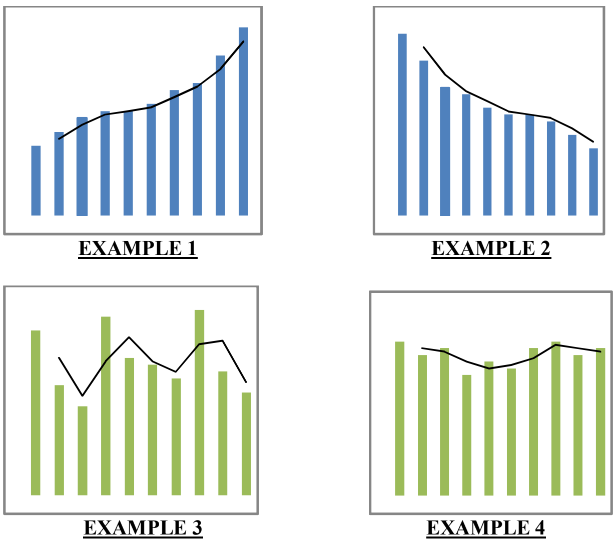


Fig. 5 Plot of number of decision points at each stage – Example 1 to Example 4

Some key observations relating to iteration can be made from the distribution of the decision points:

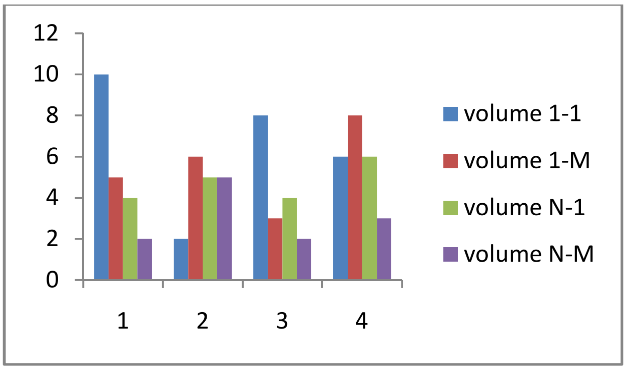
- Larger the number of decision points – more vulnerable is a stage to iteration - assumption is iteration probability is proportional to the density of the decision points.
- A trend of decreasing decision points indicates a development flow with iterations early in development flow – early stages in development more prone to iteration – (refer to Fig. 5 – example 2)
- A trend of increasing decision points indicates a development flow highly susceptible to iteration in later stages of development - may lead to late slippages to product completion – (refer to Fig. 5 – example 1)

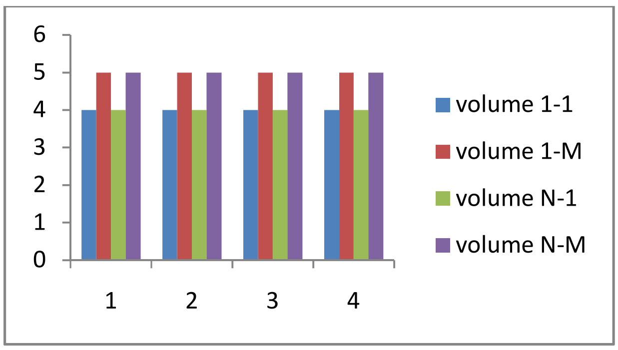
2) Metric 2 – Distribution of Volume

The visualization of the volume of decision points across different stages of the product development flow can provide useful insight into iteration probability. The classification of decision points based on volume can provide a gross level complexity involved in each decision point. A high input – output decision points are more likely to be more complex and involved.

- If the trend of increasing volume is seen - it indicates higher probability of iteration in the later stages of development as more complex decision making points are in the later stages of the development flow
- If the trend of decreasing volume is seen then it implies a lower probability of iteration in later stages of development as more complex decision making points are in early stages in the development flow

4 examples are given below in Fig. 6 of with each development flow having 4 stages of development and the decision point volume varies across the stages.





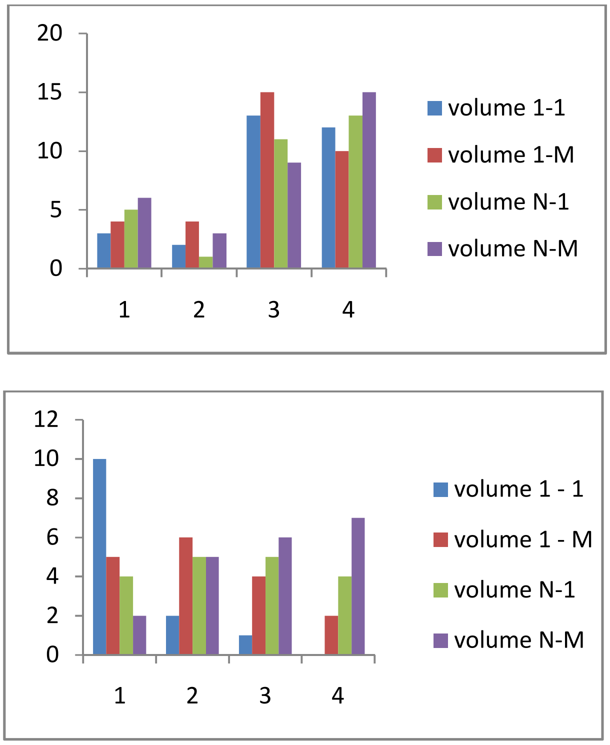


Fig. 6 Plot of number of volume of decision points at each stage – Example 1 to Example 4

Different examples have different trends of the volume of decision points. Key observations can be arrived at from the distribution of the volume of decision points across the product development stages. For example

- Volume N-M decision points later in the development flow indicates complex decision making in later stages of development – Example 3
- Low Volume N-M decision points through the product development flow indicates less complex decision making through the development flow – example 1

3) Metric 3 – Distribution of Expertise

The level of hard and soft information used for making decisions can be used to classify the decision points. Hard information is information that is more quantifiable while soft information is expertise, experience based information (the quantity of hard information (relative to soft information) increases as the knowledge about the product increases). It will be useful to see how the decision points classification based on this varies through the project progress. By mapping the human expertise involved in each decision point to a high, medium and low scale one can view how the expertise involved varies as the project progresses.

- A pattern of decreasing human expertise is preferred as the vulnerability of the decisions to change is minimized
- A pattern of increasing expertise can result in iteration later in the product development flow – may lead to iteration and rework very late in the product development flow.

3 examples are listed below in Table II.

TABLE II
3 EXAMPLES WITH VARYING EXPERTISE (LOW – 2, HIGH -10, MEDIUM -5) IN A PRODUCT DEVELOPMENT FLOW

DECISION POINTS	EX 1 EXPERTISE	EX 2 EXPERTISE	EX 3 EXPERTISE
1	2	10	10
2	2	10	10
3	2	5	10
4	2	2	5
5	5	10	5
6	5	2	2
7	5	5	5
8	10	10	2
9	10	2	2
10	10	5	2

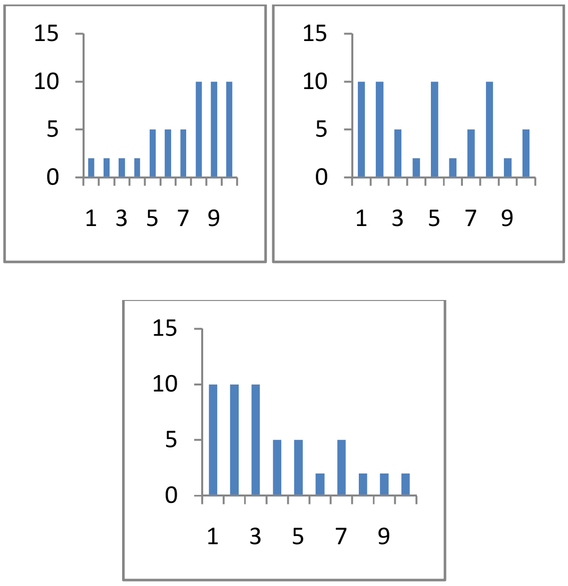


Fig. 7 Plot of expertise view across the product development flow (for the 3 examples)

3 different trends can be observed in Fig. 7. In the case of example 1 more human expertise is involved in decision making in the end, while in example 3 more human expertises is involved in decision making in the beginning. The 2 patterns are interesting – it may be possible that both the patterns are desirable.

- High human expertise involved early – may be desirable to ensure later stages are less vulnerable to changes. It is also important to note that if these decisions are verified only in the end of the development flow then it can result in significant rework – longer and costlier iteration
- High human expertise involved too late in the product development flow may result in rework of earlier stages if the decisions result in changes for the work already completed – longer and costlier iteration

4) Metric 4 Distance between Decision Points

The distance between decision points is a good indicative of the cost of iteration in a product development flow. The distance is defined as the time duration in calendar days between 2 decision points (source of the decision and destination of the decision). Source decision point is where a decision has been made and the destination decision point is where the decision is either verified or tested. 2 important observations are

- Longer the distance between decision points more costly would be the iteration – in case the rework has to happen again, there could be multiple work items impacted if the distance is too large.
- In order to have a better control over the cost of rework and schedule predictability – it is important that as the project progresses the distance between decision points are decreasing. This would mean shorter iteration at the end of the product development flow rather than a longer one.

Table III below shows 3 different patterns of product development flow where the distance between decision points vary. There are 6 decision points spread across 3 stages of development. Decision points S1 constitutes the stage 1, decision points S2, S3 constitute stage 2 and decision points S4, S5 and S6 constitute stage 3. The time of occurrence of the decision point in the product development flow is listed below – in the example 1, the 6th decision point occurs 21 calendar days from the first decision point, while in example 2 the 6th decision point occurs 130 days while in example 3 it occurs 20 days.

TABLE III
3 EXAMPLES WITH VARYING DISTANCE BETWEEN DECISION POINTS

Decision Point	Example 1 Time of occurrence	Example 2 Time of occurrence	Example 3 Time of occurrence
S1	0	0	0
S2	10	10	4
S3	15	15	8
S4	18	50	12
S5	20	80	16
S6	21	130	20

TABLE IV
3 EXAMPLES WITH SOURCE AND DESTINATION DISTANCE

Source	Destination	Example 1 Distance source to dst	Example2 Distance source to dst	Example3 Distance source to dst
S1	S3	15	15	8
S1	S2	10	10	4
S1	S4	18	50	12
S1	S5	20	80	16
S2	S3	5	5	4
S2	S4	8	40	8
S3	S5	5	65	8
S3	S4	3	35	4
S4	S5	2	30	4
S4	S6	3	80	8
S5	S6	1	50	4

In order to be able to view the distances between the decision points and to get a consistent view across the 3 examples, the distance between the decision points is normalized using the longest distance in each example (for example 1 it is 21, for example 2 it is 130 and for example 3 it is 20). The Figs. 8, 9 and 10 show the 3 patterns for the examples listed in Table III and IV.

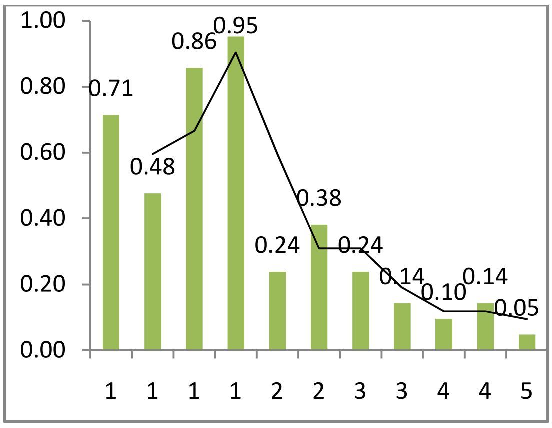


Fig. 8 Example 1: Distances reduces as project progresses

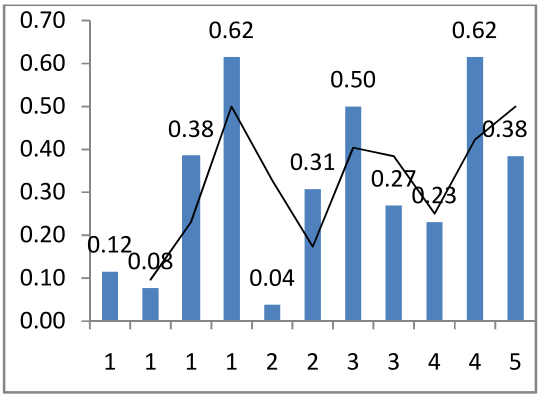


Fig. 9 Example 2: Multiple peaks as project progresses

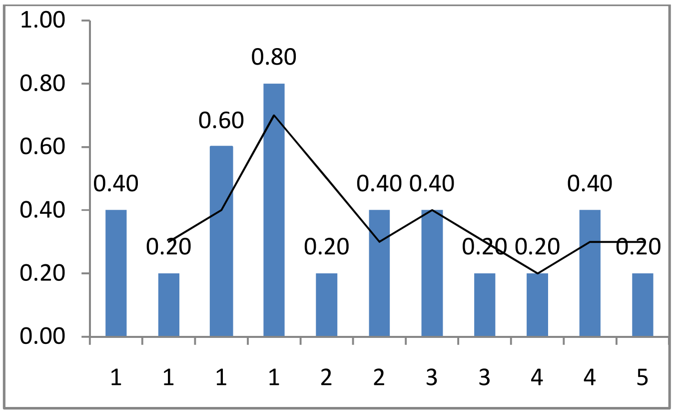


Fig. 10 - Example 3: A distribution of the distances with a single peak

The Fig. 8 indicates that in example 1 - the decision point distances are decreasing as the project progresses. In the Fig. 9 – one can see that in example 2 - the decision points with multiple peaks while in example 3 (Fig. 10) one can see a peak and then the distances reduce. Each peak indicates a high cost of iteration in case the decision needs to be reworked. Some observations from the distance measure -

- Multiple peaks indicate many iteration loops that could result in costly and longer iterations. Peaks indicate longer distance between source and destination.
- As the project progresses – an increasing distance is worrisome as most of the decision made early are verified very late in the product development flow. Any rework in this scenario may result in rework of many intermediate tasks between the source and the destination.
- As the project progresses - a decreasing distance is a welcome sign as the most of the decisions have been verified early in the product development flow and shorter iterations are likely to happen in later stages impacting few work items.

VI. Summary of the Framework using Decision Points for Iteration

Using the decision point concepts and representing the product design and development as a network of decision points one can identify the iteration probability in the design and development flow. Authors have also introduced 4 different metrics using this concept. Following key observations can be made from the study of the decision points

Key Observations

Distribution of Decision Points

- Larger the number of decision points – more vulnerable is a stage to iteration - assumption is iteration probability is proportional to the density of the decision points.
- A trend of decreasing decision points indicates a development flow with iterations early in development flow – early stages in development more prone to iteration – (refer to Fig. 5 – example 2)
- A trend of increasing decision points indicates a development flow highly susceptible to iteration in later stages of development - may lead to late slippages to product completion – (refer to Fig. 5 – example 1)

Distribution of Volume of Decision Points

- If the trend of increasing volume is seen - it indicates higher probability of iteration in the later stages of development as more complex decision making points are in the later stages of the development flow
- If the trend of decreasing volume is seen then it implies a lower probability of iteration in later stages of development as more complex decision making points are in early stages in the development flow

Human Expertise in the Decision Points

- High human expertise involved early – may be desirable to ensure later stages are less vulnerable to changes. It is also important to note that if these decisions are verified only in the end of the development flow then it can result in significant rework – longer and costlier iteration
- High human expertise involved too late in the product development flow may result in rework of earlier stages if the decisions result in changes for the work already completed – longer and costlier iteration

Distance between Decision Points

- Multiple peaks indicate many iteration loops that could result in costly and longer iterations. Peaks indicate longer distance between source and destination.
- As the project progresses – an increasing distance is worrisome as most of the decision made early are verified very late in the product development flow. Any rework in this scenario may result in rework of many intermediate tasks between the source and the destination.
- As the project progresses - a decreasing distance is a welcome sign as the most of the decisions have been verified early in the product development flow and shorter iterations are likely to happen in later stages impacting few work items.

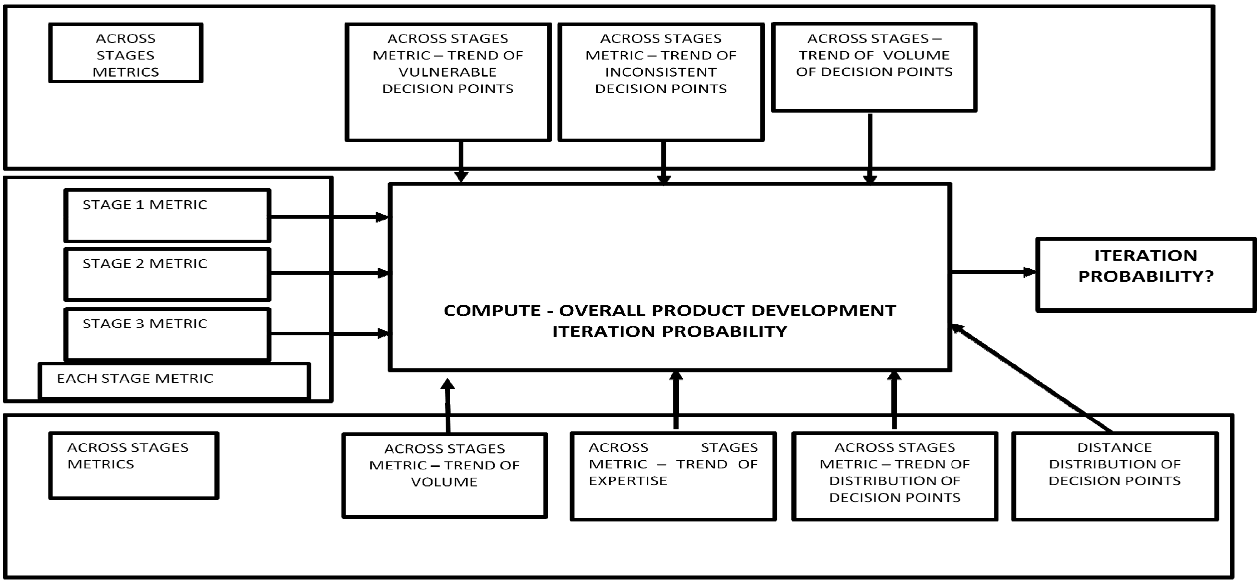


Fig. 11 Using the concept of decision points for iteration prediction

VII. Conclusion

The authors in this paper introduce the concept of decision points along with useful dimensions of decision points. A novel way to visualize the product development flow as a collection of decision points has enabled identification of metrics using these dimensions to study the iteration probability in a product development flow. In addition to providing a good insight into predicting the number of iterations in a product development flow, it can also provide useful managerial insights into probability of iteration. For instance by ensuring the right level of human expertise across the product development flow and a good distribution of decision points across the flow can make a difference in bringing unpredictable rework and iteration under control. The decision point concept and visualization of product development as a collection of decision points will bring more clarity and provide managers with a tool to anticipate rework and iteration in a more effective manner.

The concept introduced by the authors is further being investigated using case study based research. Better methods to bring the iteration under control and ensuring a predictable product development time despite the iterations can be arrived at through the case study method.

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