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DESIGN SIGNATURES: MAPPING DESIGN INNOVATION PROCESSES

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ABSTRACT
Despite variances in contexts and styles of design activity, recurrent patterns emerge in design innovation approaches and processes which lend themselves to analysis and discussion. Using a Design Innovation framework [1] that is built, in part, on the UK Council's '4D' (Discover, Define, Develop, Deliver) model of design [2], we develop design signatures, graphical maps of design innovation processes. Design signature analyses of four multi-disciplinary industrial case studies illustrate the value of design signatures as useful design activity plots that can be used to plan and manage innovation teams and activities, and to identify critical features for reflection, for clarification, and for further analysis. This work is of interest to design practitioners, managers, researchers, and educators with various motivations, such as to seek a tool to convey and analyze design innovation activity.

MOTIVATION
Design encompasses a wide range of activities and a rich set of tools that drive creative innovation across domains. It is how "new contexts, markets, and products emerge and shape worldwide practice" [3]. In our pursuit of effective design outcomes, modeling and consequently analyzing design innovation processes is a critical endeavor [4].

A number of models exist that graphically represent the design innovation process. Many models, like Ulrich and Eppinger's model of concept development [5] and Cooper's stage-gate model [6], offer useful design innovation practices but do not provide a basis to represent and analyze projects that have deviated from prescribed procedures [7]. Importantly, industry- and organization-practice projects frequently deviate from procedural models due to needs and constraints such as legacy platforms and stakeholder requirements [8]. Additionally, the location of the design or product on the S-Curve may also change the design process or even suggest specific process emphasis [24].

Other models, like Wynn's flowchart style notation [4] and the PROSUS matrix system for knowledge modeling [9] support process and knowledge management for independent projects, but are not meant to be quickly digested or used to derive insights about and between design innovation processes. It has also been noted that extant models are unwieldy in depicting design iteration loops [10].

Design innovation has been recognized as highly iterative [e.g., 11, 12]. Iterative design activities include: "iteration to progress the design; iteration to correct problems or implement changes; and iteration to enable coordination within a process, or between a process and its context" [4, 13]. Non-sequential deviations can also be expected as designers encounter blips, significant deviations, and feedback [14].

Tan et al. identified that early phase design decisions have a significant cost impact [15]. However, the lack of models for managing and reviewing iterative design innovation processes makes it difficult to accurately track, analyze, and chart design activity in a preemptive and proactive manner, which results in unpredictable project costing and scheduling [16].

The above motivated us to explore a process model of design innovation that captures iterative design effort, and that informs and supports effective planning, communication, and comparison.

We hypothesize that emergent characteristics exist across design projects that may be effectively visualized in a map, thereby enabling:

1. Understanding of driving forces behind innovation
2. Meaningful comparison of design projects
3. Formalizing of principles for effective design practice
4. Added consistency of design research and practice

We propose design signatures (or fingerprints) - stage-based maps of innovation activity based on a polar coordinate system. The elements of design signatures (*quadrant dominance, leaps, and loops*) give critical insight into the requirements (*performance, cost, and schedule flexibility*) of design projects.

We do not attempt to prescribe a recipe for successful design work, but provide an exploratory framework for analyzing and communicating design innovation.

This novel effort builds on our research in integrated Design Innovation Process Models (DIPM) [1], and we explore design signatures in this paper.

RESEARCH METHODOLOGY

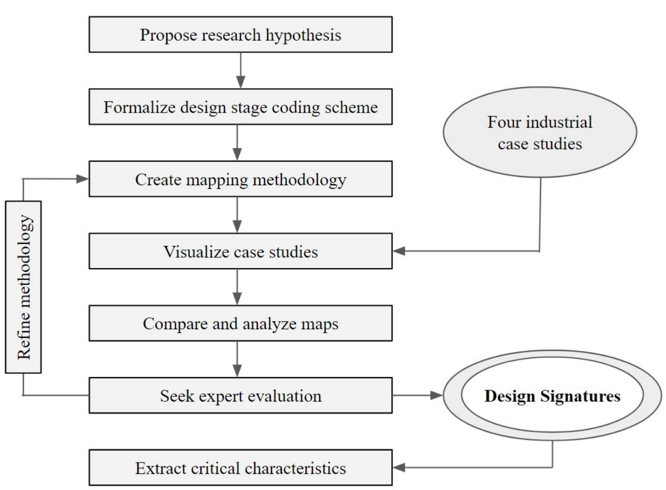


Figure 1: Research methodology

We first formalize a scheme to encode and standardize the representation and notation of design activities into four different stages, regardless of industry, application, or knowledge domain. After standardizing the data of our four multi-disciplinary industrial case studies, we map them using a design process mapping methodology, analyze the result, and seek expert evaluation. Through iterating the mapping methodology, we eventually produce design signatures. Finally, we extract generalizable characteristics. Figure 1 depicts our research methodology.

MULTI-DISCIPLINARY INDUSTRIAL CASE STUDIES

As input for process visualization and analysis, we use four industrial projects, as shown in Table I. We chose these diverse case studies so as to capture critical information about design across seemingly disparate domains, and to provide different perspectives for analysis and refinement of our final model. It is worthy to note that some of these industry projects were executed as a participatory design project, where the authors were also participants in the project.

FinTech Device

As part of the Singapore's 'Smart Nation' agenda to become a cashless society, a leading local bank tasked the design team with creating an innovative product-service that will help move the young generation onto digital payment. The multi-disciplinary design team iteratively diverged and converged on ideas, producing more than 200 prototypes, which were iteratively used to gather feedback from stakeholders through interviews and testing. Two final designs were selected and further refined through user testing and eventually designed for manufacturing.

Service Delivery

The design team led a redesign effort to evaluate the service, architecture, interior design, and workflow processes at a series of 19 service centers in Singapore [1]. The objective was to create a state-of-the-art user experience and to increase workflow efficiency. The design process started with extensive ethnographic user modeling. Following that, the team iteratively explored user needs and workflow models that they validated with users on-site and through site analysis [1]. Simultaneously, numerous co-creation sessions were conducted with the clients and end-users to generate relevant innovative concept, which were eventually prototyped on a limited scale.

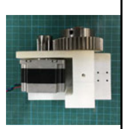
Fuel Printer

The client, Gilmour Space Technologies, tasked the design team to create a novel additive manufacturing process for use in hybrid rocket propulsion [1]. The design process for this project had a heavy focus on the systems engineering pathway [1]. The team deconstructed the project into critical subsystems, e.g. motion stage and extruder head, and employed extensive use of ideation techniques to generate concepts for each. These ideas prototyped using mockups and iterative prototypes - some up to 20 iterations - to produce a functional final product.

Workplace Transformation

A design team was engaged by a leading global investment firm to design and deliver a system for 326 employees that will augment their use of the new activity-based workspace. Concretely, the solution had to be a compact and modular kit that stores and organizes an employee's office accessories in an activity-based work environment while being easily portable. To meet an aggressive deadline and cycle time of just three weeks, the team procured, modified and combined off-the-shelf products to create the 8 prototypes. Using a Pugh chart, they then down-selected 4 designs which they refined and piloted to gather feedback from employees.

Table I: Overview of industrial case studies

Case study	FinTech Device	Service Delivery	Fuel Printer	Workplace Transformation
Industry	FinTech	Healthcare	SpaceTech	Finance
Project nature	B2B2C product	Service design	Tech. R&D	System design
Duration	6 months	3 months	12 months	2 months
Team size	4	11	2	3
Aggregate Man-hours	2816	1245	2499	363
Budget (Magnitude)	\$10^5	\$10^7	\$10^5	\$10^4
Example concept explored				

DESIGN STAGE CODING SCHEME

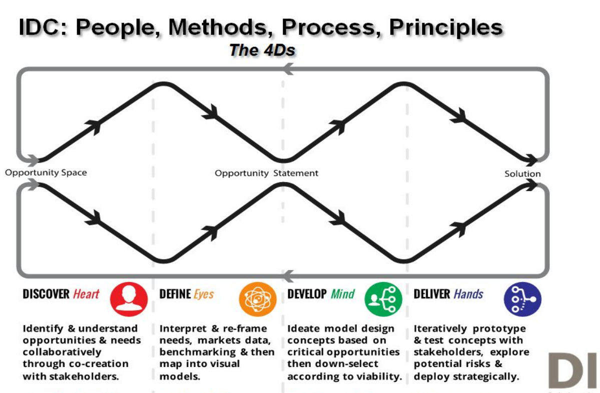


Figure 2: Overview of four 'D's design scheme, DI process, with mindsets

As with DIPM, we choose a scheme that is well supported by both literature and industry to distinctly codify various design innovation activities that were executed by the design teams [1, 2] (see Figure 2 and Table II).

Table II: Coding scheme for design activity

'D' Category	D1 Discover	D2 Define	D3 Develop	D4 Deliver
Description	Identify and understand opportunities and needs through collaboration with stakeholders	Interpret market data, benchmark results, reframe needs, and map information into abstract representations	Ideate / model design concepts, then select according to feasibility, viability, and desirability.	Prototype and test concepts, exploring potential risks, developing mitigants and deploying the result
Mindset	Empathy	Visual	Cognitive	Active
Focus	Understanding needs	Reframing opportunities	Idea / concept generation	Building and testing
Thinking mode/s	Intuition and analysis	Synthesis	Judicial thinking	Engaging prototypes judicially
Stakeholder engagement	Needs analysis	Internal stakeholder co-creation	Co-creation	Prototype interaction / assessment

With reference to project documentation, data-capture, archives, and after clarification with project participants, we classified each design activity within the case studies presented into one of the four 'D' categories. Assigned codes are shown in Annex A.

PROTOTYPING A MAPPING METHODOLOGY

Before we develop and propose a structure mapping methodology, we explore how design processes manifest themselves as plots by expeditiously prototyping a less formalized method of mapping. In this mapping prototype, we do first assign the four 'D' categories in DIPM to respective quadrants. Design activities are then linked chronologically, starting at the origin, and plotted based on their codified 'D' quadrant. We call the results 'prototype plots' because these representations quickly provide us with meaningful design information and feedback that we can draw upon to develop a more formal mapping methodology. The prototype plots are shown in Figures 3 to 6 - refer to Annex B for enlarged versions of the figure.

It is important to note that the mapping we propose models these projects as they progress through the design process to the delivery of initial functional prototypes. The maps do not follow the product to large scale manufacturing, maintenance or disposal.

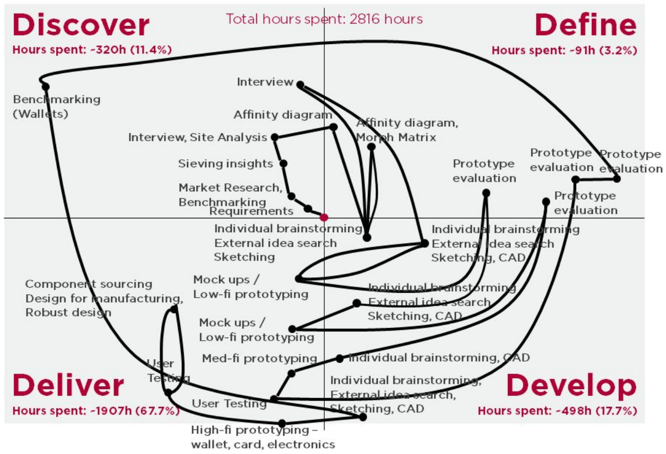


Figure 3: ***FinTech Device*** **- DIPM**

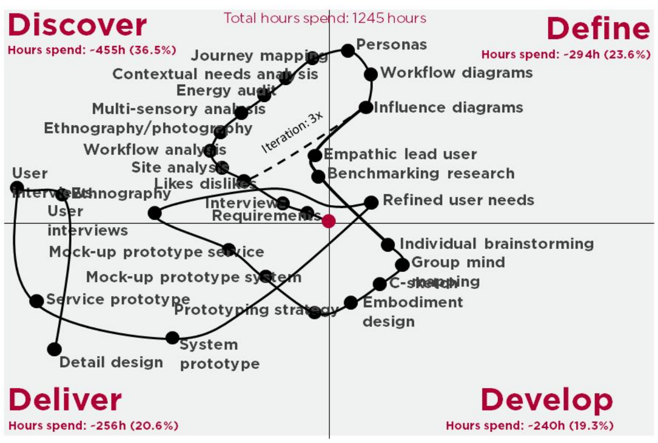


Figure 4: ***Service Delivery*** **- DIPM**

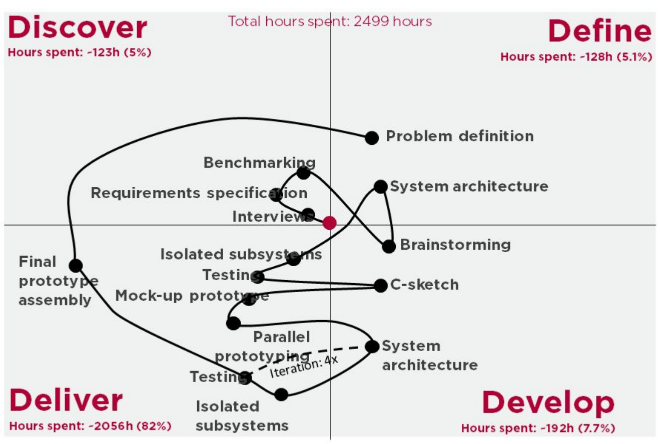


Figure 5: ***Fuel Printer*** **- DIPM**

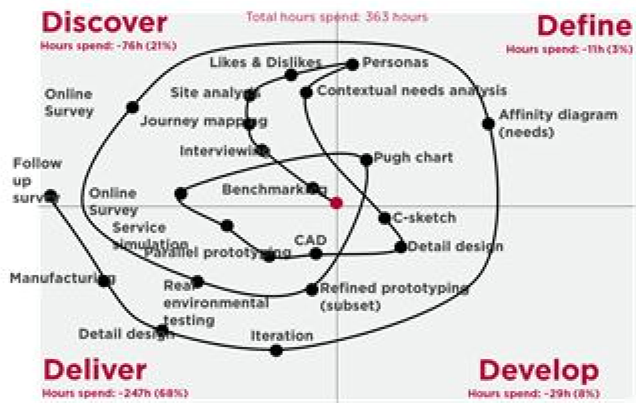


Figure 6: ***Workplace Transformation*****- DIPM**

Concordant with our initial beliefs, these prototype DIPM maps intrigue and inspire design practitioners, researchers and educators because they readily reveal insights into a project's iterative design process.

- *FinTech Device*'s map (Figure 3) depict several back and forth movement between the top quadrants and the bottom quadrants. This represents that extensive iteration on the physical prototypes was used as a tool to uncover insights and frame for foresights. Such a signature indicates deep user studies that was likely necessary due to the focus on user behaviour and demand for novelty.
- *Service Delivery*'s map (Figure 4) illustrates the presence of a loop that iterates three times between the Discover and Define quadrants. This highlights key iterations between these two phases, as substantial focus on the user experience drove the design process in the initial phases.
- *Fuel Printer*'s map (Figure 5) reveals the project's nature as a technology development project with a heavy focus on Deliver. With a total of 2074 out of 2499 hours, 83% of the design process was spent in the Deliver quadrant. This is result of extensive physical prototyping that took place during the project with the aim of demonstrating a technical proof of concept.
- *Workplace Transformation* was a rapid response and innovation project with extremely short cycle time between design brief and full delivery of manufactured goods. Its map (Figure 6) shows a heavy emphasis and multiple iterations between Discover and Deliver, which is due to the team's deep focus on user experience.

These prototype plots reveal the potential of DIPM mapping to be a powerful planning and analysis tool that enriches the design process. Much of the work in this paper is dedicated to extending DIPM by formalizing a mapping methodology (design signatures) to create benchmarks for easy comparison, communication, and analysis. Later discussion on design signatures will provide richer, more refined, and higher fidelity insights based on the case studies.

DESIGN SIGNATURE MAPS

After investigating a diverse set of presentations and approaches, and after several iterations, we created a formalism for any design innovation process to be mapped. The following outlines the Design Signature procedure prescribed to systematically generate design signatures.

Collecting Input Data

While the design project is ongoing:

1. Record time spent for each activity by each team member and list them in a chronological order, approximating it to the nearest number of hours.
2. Classify each activity under the 'D' Category it should fall under (Discover, Define, Develop, or Deliver) according to the metrics spelled out in Table II.

Table III shows an example of a list of number of hours spent in 3 activities by 3 people.

Table III: Input data table example illustration

Design Activity	Person A	Person B	Person C	Total	'D' Category Classification
Requirements	30 h	20 h	20 h	70 h	D1 (Discover)
Interviews	20 h	20 h	27 h	67 h	D1 (Discover)
Personas	5 h	10 h	10 h	25 h	D2 (Define)

Mapping Design Signatures

While we recommend mapping the design signatures as the project progresses so the team can get insights in their DIPM thus far, it is also possible to map the design signatures retrospectively once the project is completed. Here we will describe the steps involved in mapping the Design Signatures:

1. Cluster the activities: Consider each activity chronologically, grouping the activities together when they fall under the same 'D' Category, and creating a new group each time the 'D' Category of the activity changes.
2. Sum up the total time spent in each activity cluster and the cumulative hours spent after each activity cluster, and list them chronologically. If the project is completed, calculate the cumulative percentage of time spent (i.e. time elapsed in the project). Table IV shows one such example, where activity clusters were listed chronologically from left to right, where D1, D2, D3 and D4 represent Discover, Define and Develop and Deliver, respectively.

Table IV: Design activities time records: Service Delivery project (truncated)

'D' Category	D1	D2	D3	D4	D1	...
Hours spent within one design phase	137	25	0	0	62	...
Cumulative hours spent (time elapsed in project after each design phase)	137	137+25 = 162	162+0 = 162	162+0 = 162	162+62 = 224	...

Establishing the coordinates system

3. Construct the horizontal and vertical axes, and demarcate each quadrant according to its 'D' Category as seen in Figure 7. Determine an appropriate scale for the number of hours for your graph, noting that the radius of the curve represents time elapsed in the project. For example, if the cumulative the number of hours spent on the project is 500 hours, then the limits of both axes should be 500.

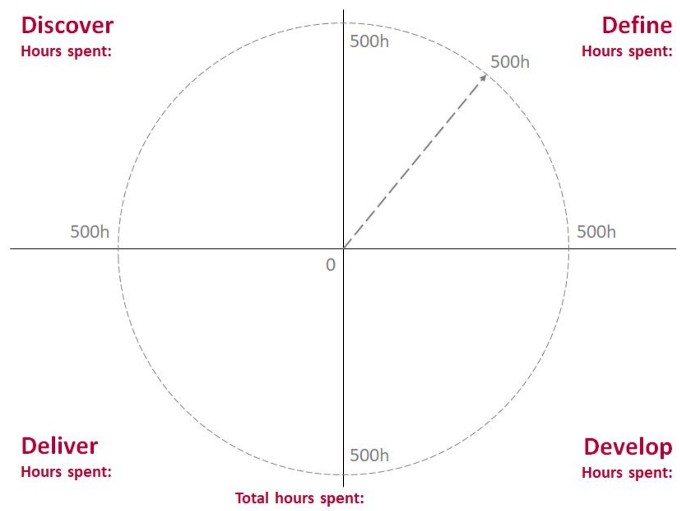


Figure 7: Setting the stage with axes and quadrants

At this juncture, it is important to establish that we are using a polar coordinate system. The radius (r) from the center of the plot would define the cumulative project time elapsed, in hours, up till that data point (activity cluster). The angle (θ) indicates which 'D' phase the activity cluster is executed in. The change in radius in each quadrant would represent the amount of time spent in a 'D' category. The zero-degree line of the polar coordinates system is located on the equivalent of the positive x-axis in a Cartesian coordinates system, which θ increasing anti-clockwise. Table V shows a summarized comparison between the two variables of the polar coordinates.

Table V: Design signature variables

	Context	Description	Plot variable	
Independent Variable	'D' Category	Discover, Define, Develop, or Deliver	θ	Angle
Dependent Variable	Cumulative Hours*	Project time elapsed up to and including data pt.	r	Radius

*If project is completed, *Cumulative %* may be preferred for normalized plots

Concretely, a point on the plot with coordinates [300, 120] indicates an ongoing activity cluster in the Discover phase that is at the 300-hour mark of the entire project, while a point on the plot with coordinates [40, 0] would indicate and activity cluster at the 40-hour mark of the entire project that has either just concluded the Define phase or just starting the Develop phase. We will later introduce the use of arcs rather than data points to better represent activity clusters.

Plotting the Design Signature

4. Plot the graph based on the design activity time records - mark out the cumulative number of hours taken after each activity cluster on the "End axis" of its 'D' Category, as illustrated in Table VI and Figure 8. For example, if the activity cluster falls under "D1", it should be marked on the top side of the vertical axis.

Table VI: Quadrant Labels

Design Phase	'D' Category	Quadrant	Angle (anti-clockwise from right axis)	Start Axis	End Axis
Discover	D1	1	θ=90°	Left	Top
Define	D2	2	θ=0°	Top	Right
Develop	D3	3	θ=270°	Right	Bottom
Deliver	D4	4	θ=180°	Bottom	Left

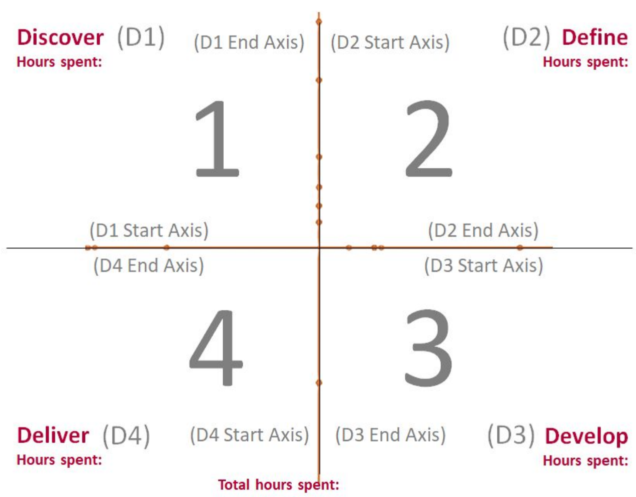


Figure 8: ***Service Delivery*** **- Time spent marked on axes**

The dots are plotted on the axes to indicate the ending point of each phase. They will later be connected by an arc that spans the corresponding quadrant - representing the execution of a phase.

5. Starting at the origin, sequentially connect plotted points (dots) with variable radius arcs. Each end of the arcs should touch the respectively axes perpendicularly.
   a. For the first arc, which starts at the origin, draw a semi-circle arc clockwise from the origin to the first data point, as illustrated in Figure 9.

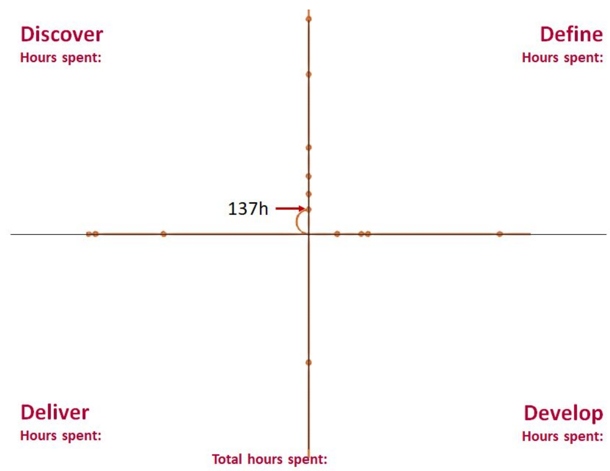


Figure 9: Service Delivery - first arc connected

   b. Subsequently,
      i. if the next 'D' Category is non-zero, draw a 90º variable radius arc clockwise to the next point, as illustrated in Figure 10.

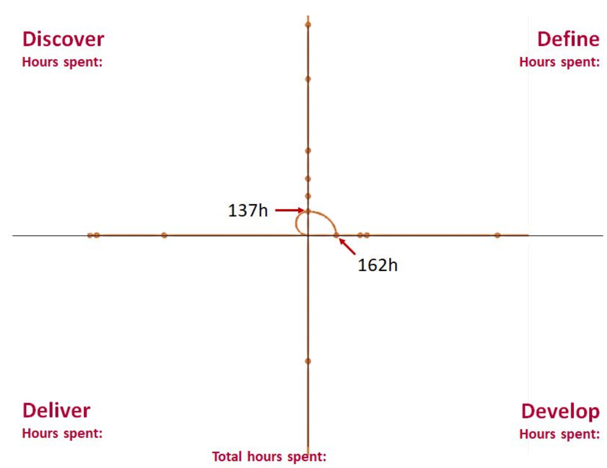


Figure 10: Service Delivery - Second arc connected

ii. if the next ‘D’ Category is zero, draw a dotted line fixed radius circular arc clockwise across the quadrant that are skipped (e.g. D3 (Develop) and D4 (Deliver) is skipped in the Service Delivery Case), as illustrated in Figure 11.

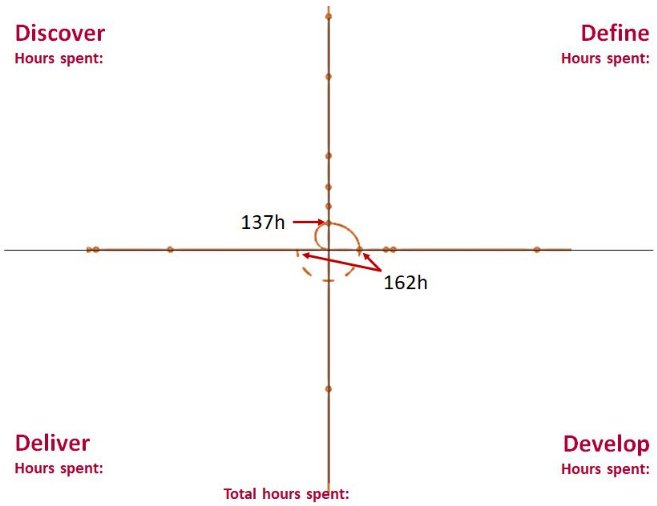


Figure 11: Service Delivery - first quadrant skip

c. Label the number of hours spent in each ‘D’ Category for the entire project.

Refer to Figure 12 for an example.

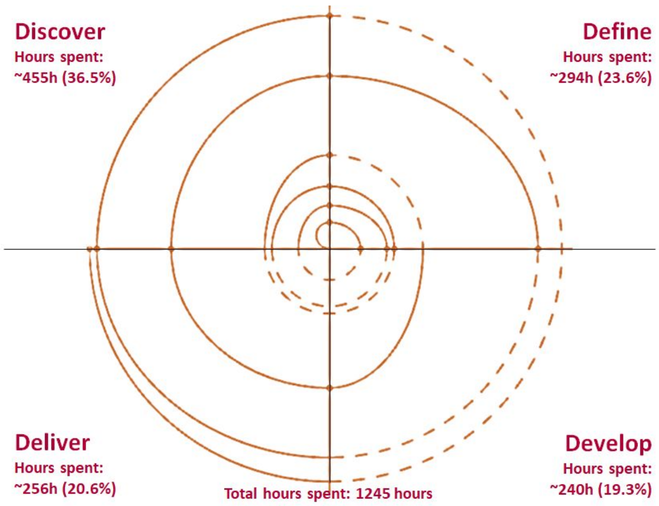


Figure 12: *Service Delivery* - Dots connected

6. (Optional) Label design activities at regular intervals along the respective arcs within their codified ‘D’ category (refer to Annex C to view our 4 industrial case studies with these labels).

7. (Optional) Append a stacked bar chart depicting the percentage of hours spent per ‘D’ category.

Moe et al. postulate that project requirements (cost, schedule, and performance) are vectors of flexibility (0: flexible, 1: rigid) [18]. This approach provides a useful analogy for analyzing design signatures. The four case studies are defined from each vectoral standpoint in Table VII, which supports the short discussions following each design signature map in Figures 13 to 16.

Table VII: Case study requirement flexibility

Project Vectors (Requirements)	FinTech Device	Service Delivery	Fuel Printer	Workplace Innovation
Cost	0	1	1	1
Performance	0	0	1	0
Schedule	0	0	0	1

Legend - 0: Flexible, 1: Rigid

To explain how the project flexibilities were assessed and Table VII constructed, we will briefly discuss two projects. FinTech has flexibility in all 3 aspects as margins were built into the timeline and budget from the onset. Additionally, there was room for innovation and free-play given the broad project goal. Conversely, Fuel Printer had a well-defined technical outcome, resulting in no performance flexibility. There was no cost flexibility because the budget for developing several technical subsystems was tightly managed. However, as it is a technology development project with no urgent need to go-to-market, there was substantial flexibility in its schedule.

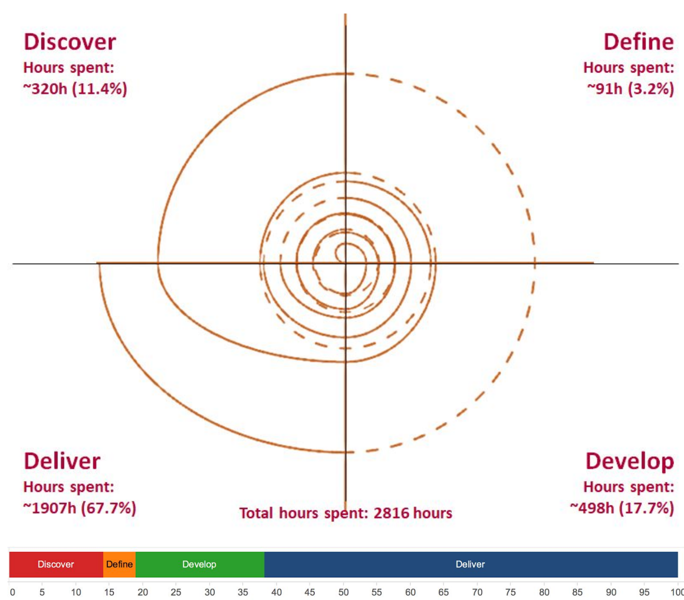


Figure 13: *FinTech Device* - Design signature

Immediately apparent in the *FinTech Device* design signature (Figure 13) - refer to Annex C for fully labelled diagram - are its multiple *loops*. These can be attributed to multiple design review sessions requested by the client, and the built-in cost, performance, and schedule flexibility in the project. The team leveraged this design freedom to explore numerous user needs and test experiments over 200 prototypes, which converged to the delivered final product after several iterations [19].

The *FinTech Device* scenario is an example of a design innovation project where a high quantity of rapid and numerous iterations were both expected and beneficial. These iterations allowed the team to progressively develop key insights and to successfully develop a final product system that exceeded the expectations of their clients and stakeholders.

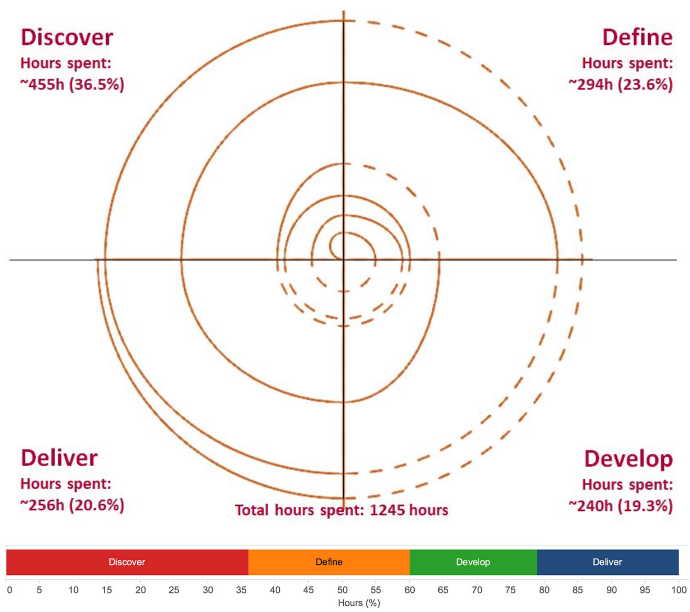


Figure 14: *Service Delivery* - Design signature

In the *Service Delivery* design signature (Figure 14) - refer to Annex C for fully-labelled diagram - we see a distinctive semi-circle pattern at the start of the project (axes origin). This indicates that in the early stages of the project, the team oscillated a number of times between the Discover and Define phases without proceeding into the Develop or Deliver phase. This is a consequence of the cost rigidity of this particular project, which required the team to be prudent about advancing into a costly development phase before achieving some measure of certainty. Moreover, this project had a level of schedule flexibility, which allowed the design team to carry out several Discover-Define iterations. Towards the end of the project, when new user insights were discovered, the team skipped the Define and Develop phases and leaped directly into Deliver to iterate on their final prototypes.

Of the four projects analyzed, the *Service Delivery* project is the most even in terms of hours spent between each of the four 'D' categories, but yet has a focus in Discover and Deliver given the user experience centricity of the project.

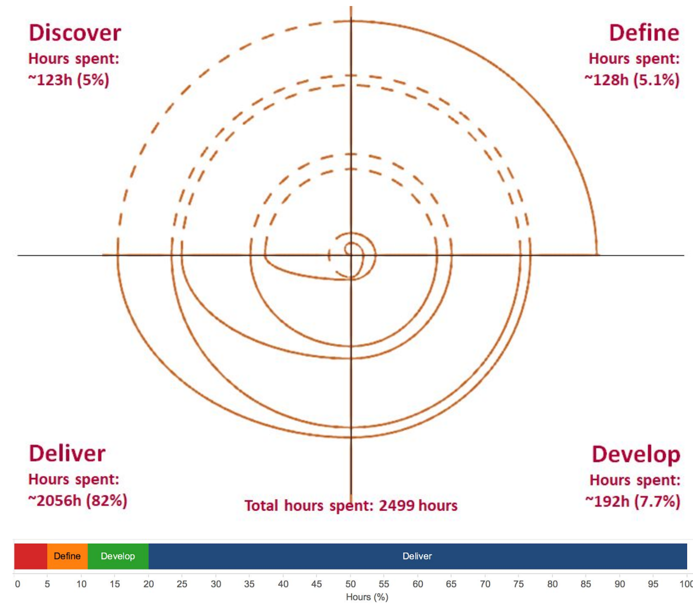


Figure 15: *Fuel Printer* - Design signature

It is evident from the *Fuel Printer* design signature (Figure 15) - refer to Annex C for fully labelled diagram - that activity was mostly categorized in the Deliver and Develop phases. In fact, the project team never returned to the Discover phase after the very first activity. From a time perspective, over 80% of the time was spent in the Deliver phase.

These observations allude to the project's performance inflexibility, the fact that highly specified requirements were already developed by the client, a space technology company. Hence there was no need to do user discover or redefining the requirements. Consequently, the team consequently placed "a heavier focus on the systems engineering pathway" and technology development, proof-of-concept, and validation [1].

In the final step of the project, the map concludes in the Define phase as the team was tasked to propose next steps in the development of a broader hybrid rocket technology, while retaining the user interface and system evolution in future projects [1].

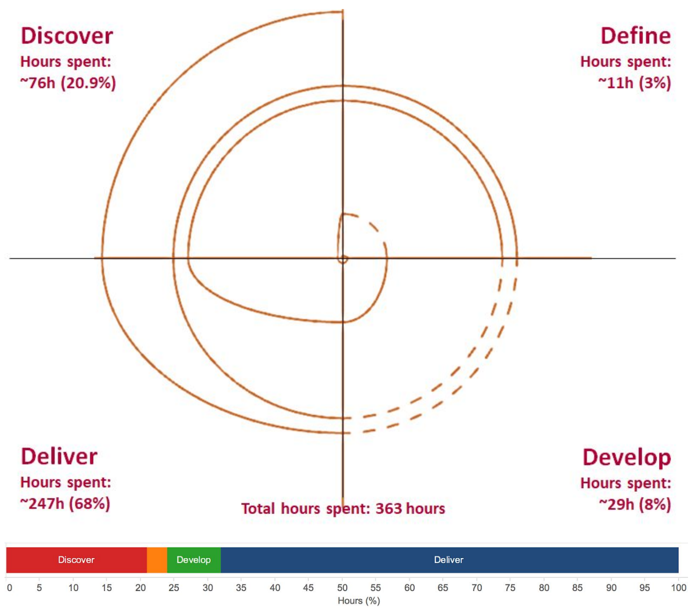


Figure 16: *Workplace Transformation* - Design signature

Of the four design signatures presented, the *Workplace Transformation* design signature (Figure 16) - refer to Annex C for fully labelled diagram - shows the least number of iterations. This is due to its schedule rigidity, and the effect is exacerbated by its cost rigidity. As Moe et al. indicates, rigidity in schedule necessitates less rework and fewer iterations [18]. Additionally, the lack of cost flexibility entails *leaps*, particularly across the Develop phase, due to the lack of project resources required for development.

Ultimately, the spatial dimension of design signatures corresponds with project progress in a way that reveals insight about:

1. Emphasis and order of stages (*quadrant dominance*)
2. Iterative revisiting of stages (*loops*)
3. When an event catalyzes the need to get to a different point in the design process (*leaps*)

Design project stakeholders will find it insightful to keep track of how a project progresses through each of the four 'D' categories, keeping in mind the flexibility requirements of their respective projects. For instance, a project manager on a rigid schedule should aim to avoid unwanted loop-backs that could prove costly [6]. *Quadrant dominance*, *loops*, and *leaps* visually represent pertinent elements of the design journey, and we have summarized how these dimensions get affected in Table VIII.

Table VIII: Project requirements - effect on design signatures

Proj. Requirement	Flexible	Rigid
Cost	More *loops*	More *leaps*
Performance	Higher component of D1 / D2 than other projects	Higher component of D3 / D4 than other projects
Schedule	More *loops*	Fewer *loops*

It is also useful to consider the project implications presented by Moe et al. [18], which are based on how a design team would likely undertake a project "at the extremes of requirement flexibility", but can be extrapolated for most design cases. Table IX is extracted from [18] and presented analogously to Table VIII for ease of reference.

Table IX: Project requirements - implications on the project [18]

Proj. Requirement	Flexible	Rigid
Cost	Should use multiple efforts	Should only use a single effort
Performance	No iteration should be performed	Should use iteration(s)
Schedule	Should rework the plan	Should use only a single plan

Annex D presents several alternative mapping approaches explored (three-dimensional design signatures, stepped design signatures, and *bouncing ball* model).

DISCUSSION OF IMPORTANCE

As Wynn suggests, graphical approaches to process modeling, such as the proposed design signatures, can be easily understood by most, and remain flexible enough for a model to "be constructed at different levels of rigor and formality according to the modeller's needs and preference" [4].

Additionally, data required for design signatures is not involved. The task of creating a design signature map does not add a huge burden to the documenter or the modeler, and is an excellent way to keep track of and to remain accountable to project progress.

We note that others have attempted to evince the iterative nature of the design process with visually comparable forms, such as those used to procedurally describe the innovation process in naval architecture [20] and software engineering [22].

However, design signatures are not merely spirals. Design signatures map out the process taken by design innovation, which may be characterized by the visual elements of *loops,* *leaps,* and *quadrant dominance.* Additionally, as the basis of design signatures is the ubiquitous and widely accepted four 'D's design coding scheme, design signatures can thus be used for a wide range of projects and emergent contexts, from service and systems design, to engineering product development.

Moreover, design signatures are a powerful departure from existing process models due to the formers' ability to serve as a basis for comparison between projects. This means that those involved in design practice can model their innovation process after successful projects with similar contexts.

Before a design project, managers can use elements of the plot to chart a preemptive approach to design activity based on project performance, costing, and scheduling. However, a static model for design is insufficient. During the project, design signatures can be used to clarify and even dynamically modify paths taken by design teams. After the completion of a project, design signatures are an excellent tool for retrospective reflection and analysis of design work.

LIMITATIONS

A number of limitations should be noted regarding the study presented in this paper:

1. Concurrent processes with multiple parallel chains or interdependent design issues that must be simultaneously considered may not be readily mapped in a single neat chronology [22].
2. Projects mapped in this paper are significant and industry-client based, but run below 3000 man-hours. Design signatures of larger or more complex projects may become more unwieldy for quick sense-making.
3. Subjectivity about the classification of the four 'D' categories may arise, resulting in semantic incommensurability and an inability to compare between design signatures. However, this can be easily overcome by agreeing on formal matrices such as that presented in Table II, and by using statistically significant results of inter-rater reliability methods.
4. As the radius of a design signature map increases, its arc naturally grows. This visual effect carries a potential, unintended consequence that viewers may perceive processes that take place later in the design process to take a longer time. This is not necessarily the case.
5. Design signatures do not portray to an external perceiver the circumstances that result in *quadrant dominance, loops,* or *leaps*. For instance, the resignation of a key team member, co-creator or change of client-side point of contact may lead to *quadrant dominance* or necessitate a more significant number of *loops*, but this is not conveyed in a design signature. One solution is to use design signatures in tandem with micro-level analytical models [4] such as Blessing's PROSUS [9] or Design History System (DHS) proposed by Shah et al. [23].

CONCLUSIONS AND FUTURE DIRECTION

We propose design signatures as a strategic tool for design practitioners, managers, researchers, and educators. Design signatures have an obvious application in communication, analysis, and education. The wealth of information and actionable insights that can be extracted from these maps reveals its enormous capacity to increase the efficacy of design innovation.

Looking ahead, it is pertinent to develop a manner for modelers to represent additional contextual information across concurrent processes. It would also be interesting to further test the robustness and usefulness of design signatures in supporting and improving design processes (e.g. efficiency, resource allocation, cycle time). This study could be supported by a survey of design practitioners and researchers on their reflections about design signatures. Additionally, we would like to map more industrial projects and extract useful archetypes for the conducting of ever more effective design innovation.

Through working with the four industrial and multi-disciplinary case studies presented in this paper, the team hypothesizes that archetypes may arise by classifying projects through design-dependent factors such as feasibility, viability, and desirability. We have already observed that *Service Delivery*, a service design project high on the viability requirement and with a strong emphasis on user connection, exhibits significant Discover *quadrant dominance.* On the other hand, *Fuel Printer,* a technology project with relatively minimal ethnographic requirements and strict requirements on feasibility, displays extreme Develop *quadrant dominance.* Another lens by which archetypes may arise is by considering whether an innovation project is technology- or market-driven, whether it is an exploratory or rapid response, and whether it is a product or system design.

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ANNEX A

CODES ASSIGNED FOR FOUR CASE STUDIES

Payment Device

1. Requirements
2. Market Research
3. Benchmarking
4. Sieving Insights
5. Interview
6. Site Analysis
7. Affinity Diagram
8. Interview
9. Individual Brainstorming
10. External Idea Search
11. Sketching
12. Affinity Diagram
13. Interview
14. Individual Brainstorming
15. External Idea Search
16. Sketching
17. CAD
18. Mock Ups
19. Parallel Prototyping
20. Prototype Evaluation
21. Prototype Evaluation
22. Interview
23. Individual Brainstorming
24. External Idea Search
25. Sketching
26. CAD
27. CAD
28. Mock Ups
29. Parallel Prototyping
30. Prototype Evaluation
31. Prototype Evaluation
32. Individual Brainstorming
33. CAD
34. CAD
35. Mock Ups
36. Parallel Prototyping
37. User Testing
38. Prototype Evaluation
39. Benchmarking
40. Individual Brainstorming
41. External Idea Search
42. Sketching
43. CAD
44. Parallel Prototyping
45. Component Sourcing
46. Design for Manufacturing
47. Robust Design
48. User Testing
49. Interview
50. Survey
51. Component Sourcing
52. Design for Manufacturing
53. Robust Design

Service Delivery

1. Requirements
2. Interviews

On Site Location X3 Site

1. Likes Dislikes
2. Site Analysis
3. Workflow Analysis
4. Ethnography/Photography
5. Multi-sensory Analysis
6. Energy Audit
7. Contextual Needs Analysis
8. Journey Mapping

Studio Design

1. Personas
2. Workflow Diagrams
3. Influence Diagrams
4. Benchmarking (Physical Site, And Industrial Publications)
5. Individual Brainstorming
6. Group Mind Mapping
7. C-sketch
8. Embodiment Design
9. Prototyping Strategy
10. Mock-up Prototype System
11. Mock-up Prototype Service

On Site Location X1 Site

1. System Prototype
2. Service Prototype

Studio Design

Detail Design

Fuel Printer

On Site Location

1. Interview
2. Requirements Specification

Studio Design

1. Brainstorming
2. Benchmarking
3. Paper Prototyping
4. Subsystem Isolation

Composite Subsystem

1. Testing
2. C-sketch
3. Mock-up Prototype
4. Isolated Subsystem Prototype
5. Parallel Prototypes
6. Iteration
7. System Architecture
8. Final Prototype Assembly
9. Testing

FDM Subsystem

1. Cad
2. Benchmarking
3. Prototype
4. Testing
5. Isolated Subsystem Prototyping

Iteration

Workplace Innovation

Studio Design

1. Benchmarking

On Site Location

1. Journey Maps
2. Site Analysis
3. Likes And Dislikes
4. Personas
5. Contextual Needs Analysis

Studio Design

1. C-sketch
2. Detail Design
3. Cad
4. Parallel Prototyping
5. Service Simulation
6. Pugh Chart

On Site Location

1. Refined Prototyping (Subset)
2. Real Environmental Testing
3. Online Survey

Studio Design

1. Affinity Diagram (Needs)
2. Iteration
3. Detail Design
4. Manufacture

ANNEX B

PROTOTYPE PLOTS

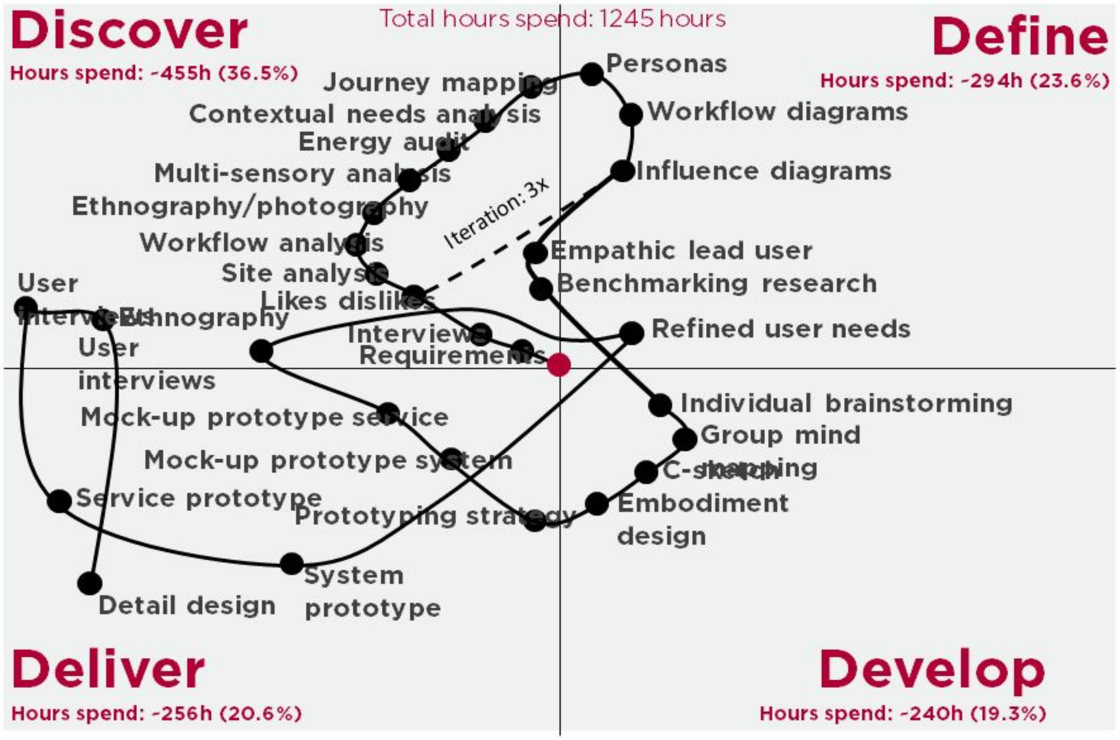

Figure B-1: Service Delivery prototype plot

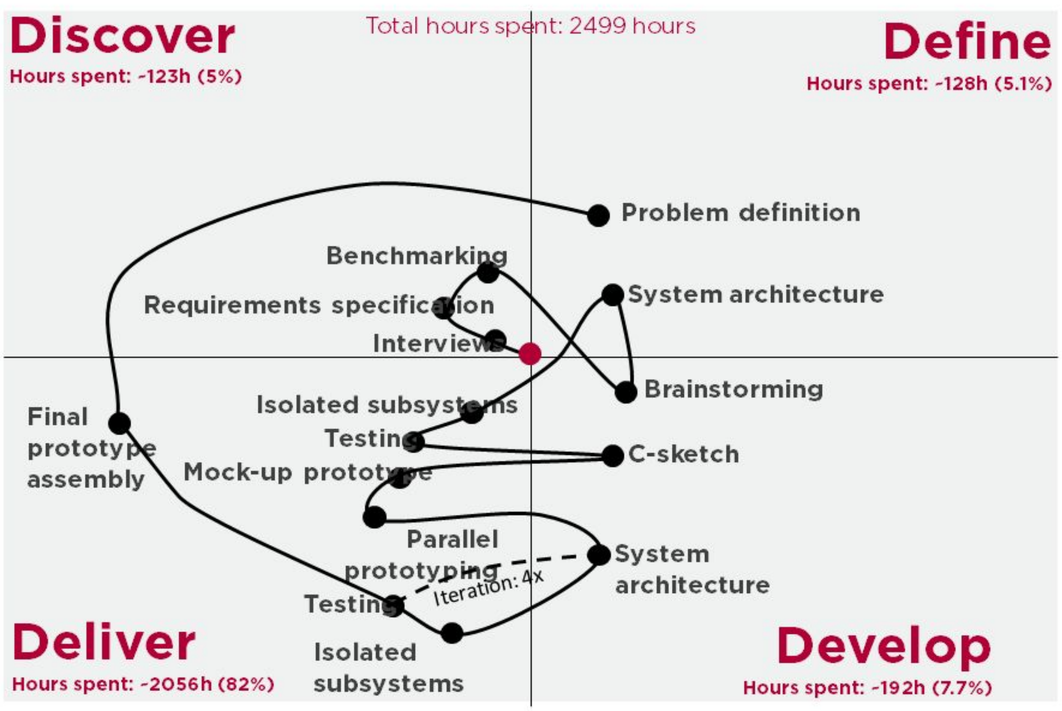

Figure B-2: Fuel Printer prototype plot

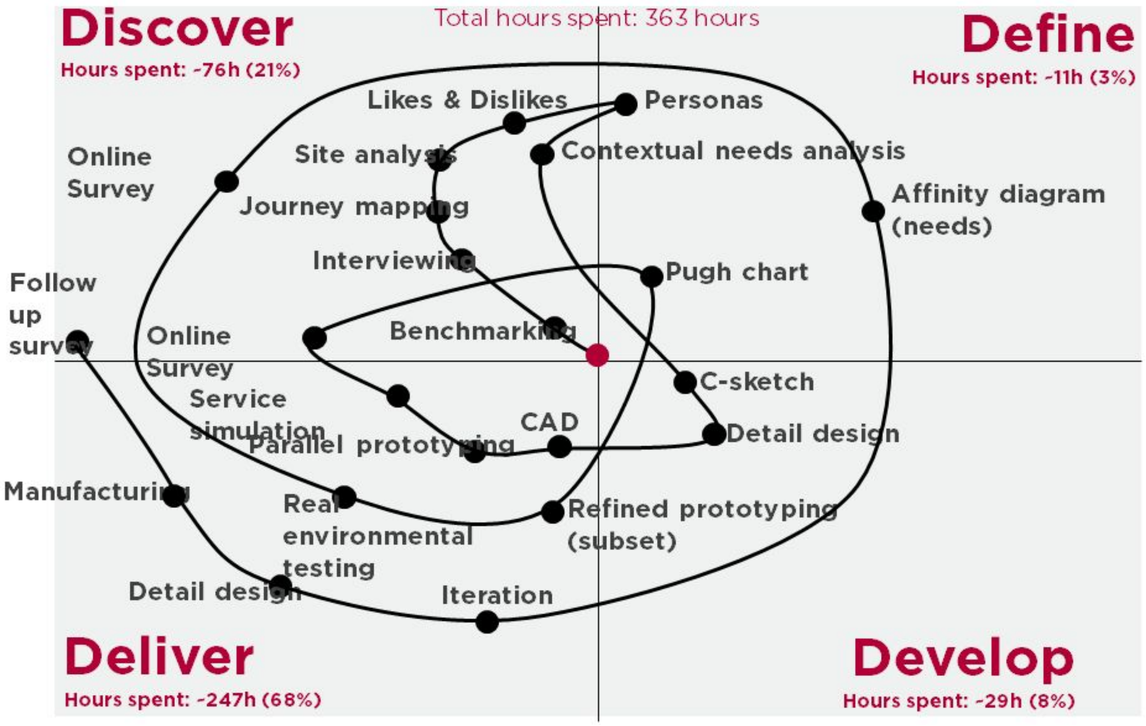

Figure B-3: Workplace Transformation prototype plot

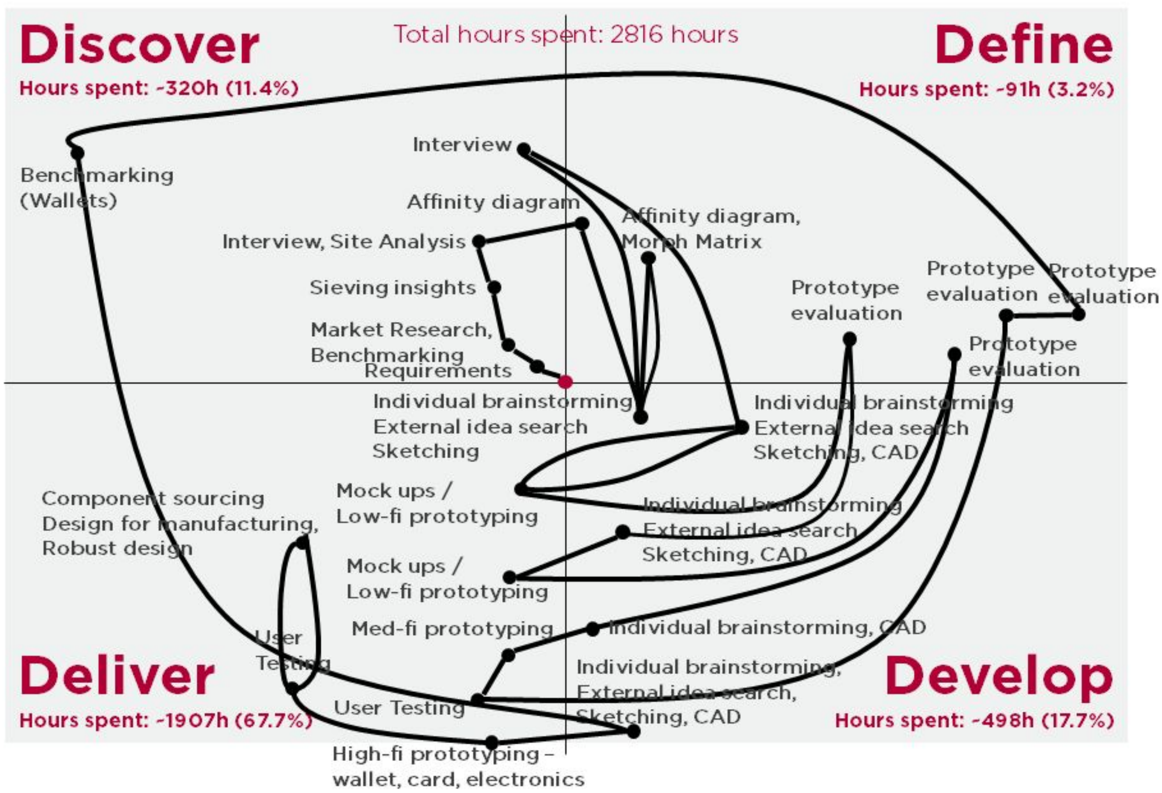

Figure B-4: Fintech Device prototype plot

ANNEX C

DESIGN SIGNATURES OF THE 4 INDUSTRIAL CASES STUDIES - WITH ACTIVITY LABELS

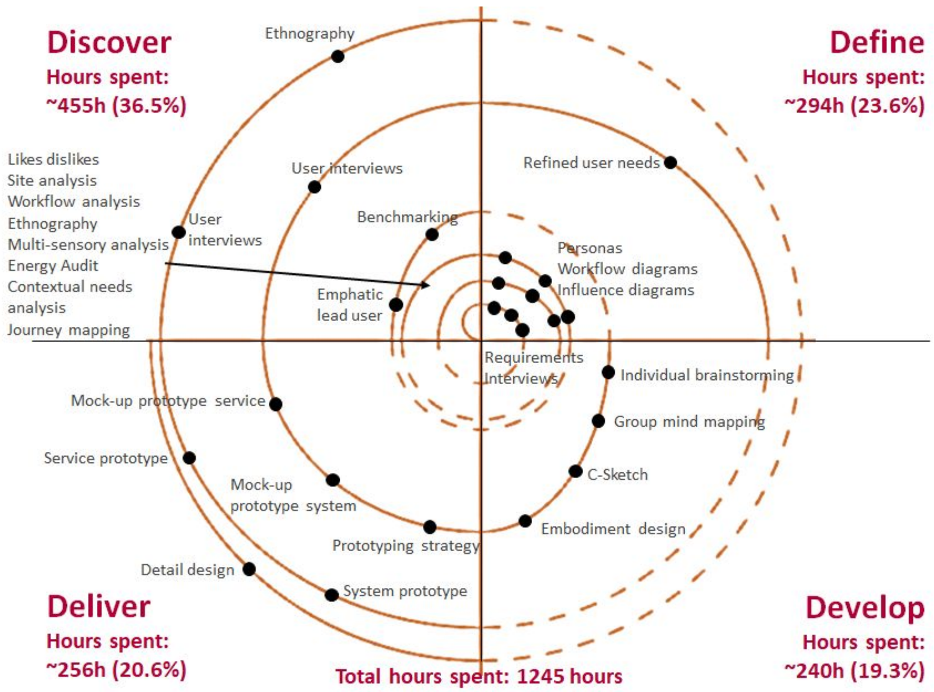

Figure C-1: Service Delivery design signature, fully labeled

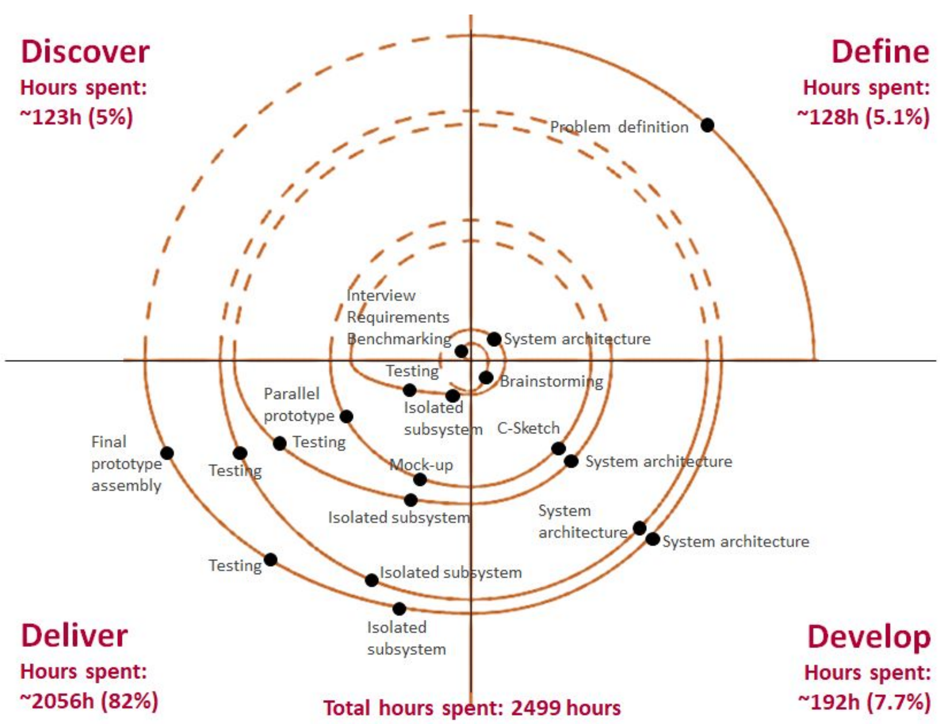

Figure C-2: Fuel Printer design signature, fully labeled

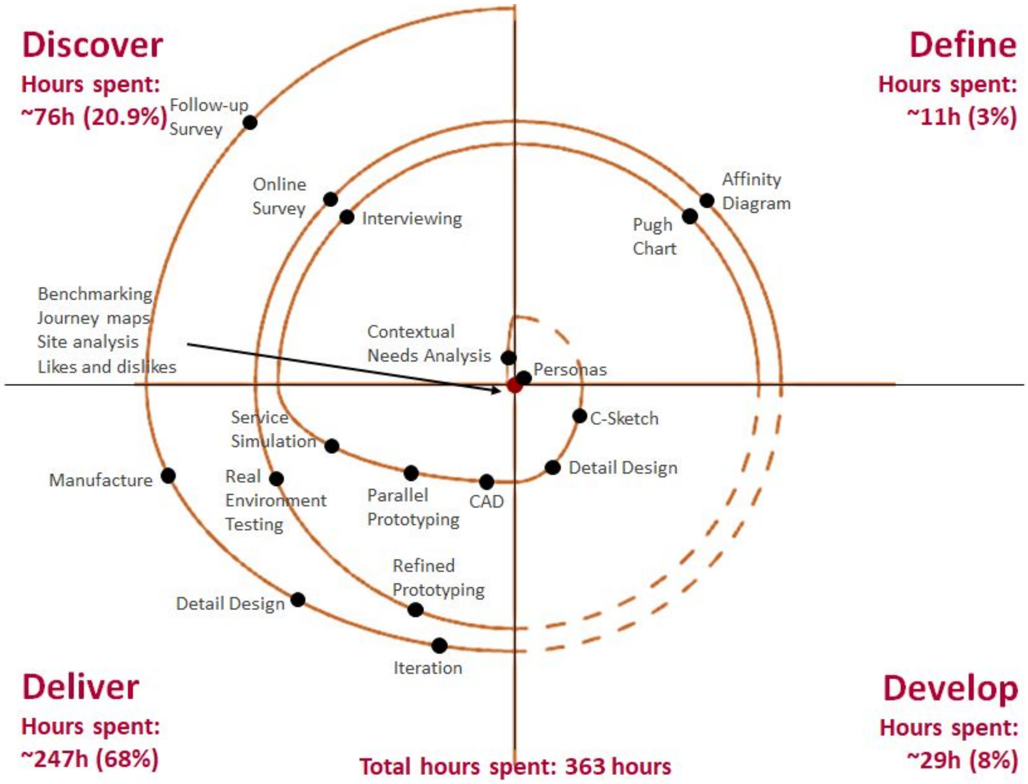

Figure C-3: Workplace Transformation design signature, fully labeled

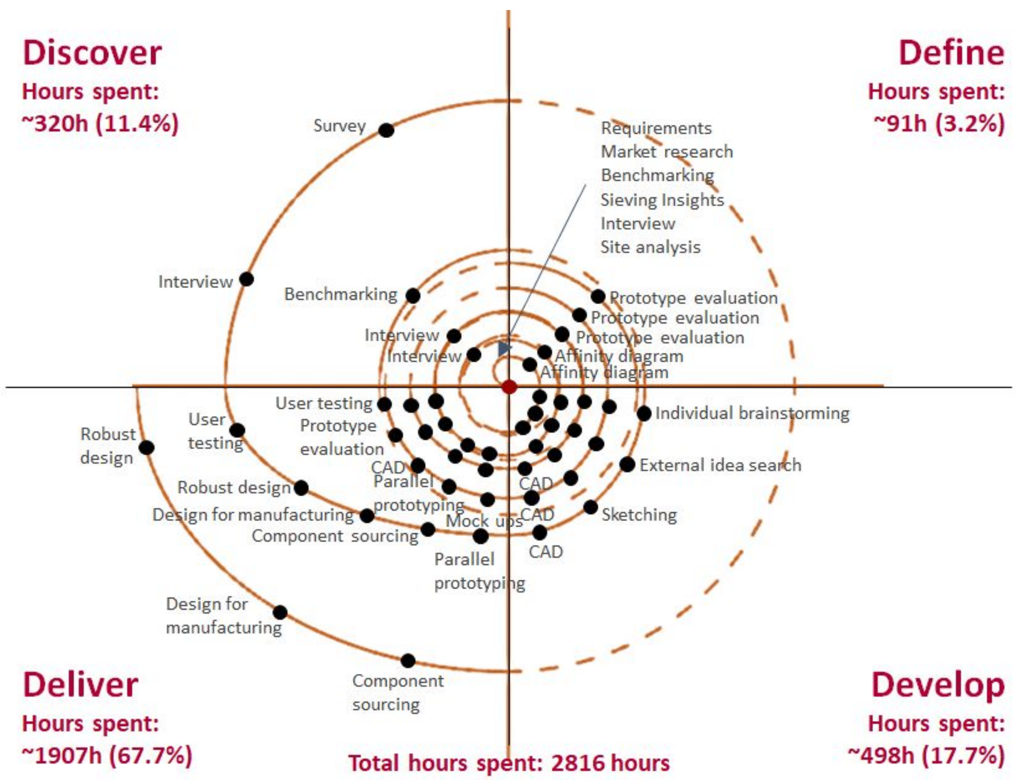

Figure C-4: Fintech Device design signature, fully labeled

ANNEX D

ALTERNATIVE MAPPING APPROACHES EXPLORED

The team iterated through numerous mapping approaches before selecting design signatures, which ultimately provided readers with the best sense of the progress of a design project and its iterations. We present three other mapping approaches (three-dimensional design signatures, stepped design signatures, and *bouncing ball* model) which garnered significant positive review, but were not ultimately chosen due to reasons discussed below.

THREE-DIMENSIONAL DESIGN SIGNATURES

This three-dimensional version of design signatures was conceived to provide users with an additional sense of elapsed time. A cylindrical coordinate schema was used. r and θ remain the identical to that used in design signatures (Figure 8), while the z-dimension is also used to represent time. However, the resulting maps were unintuitive to most, and *leaps* were obscured in certain planes. Please refer to Figure A-1 for an example.

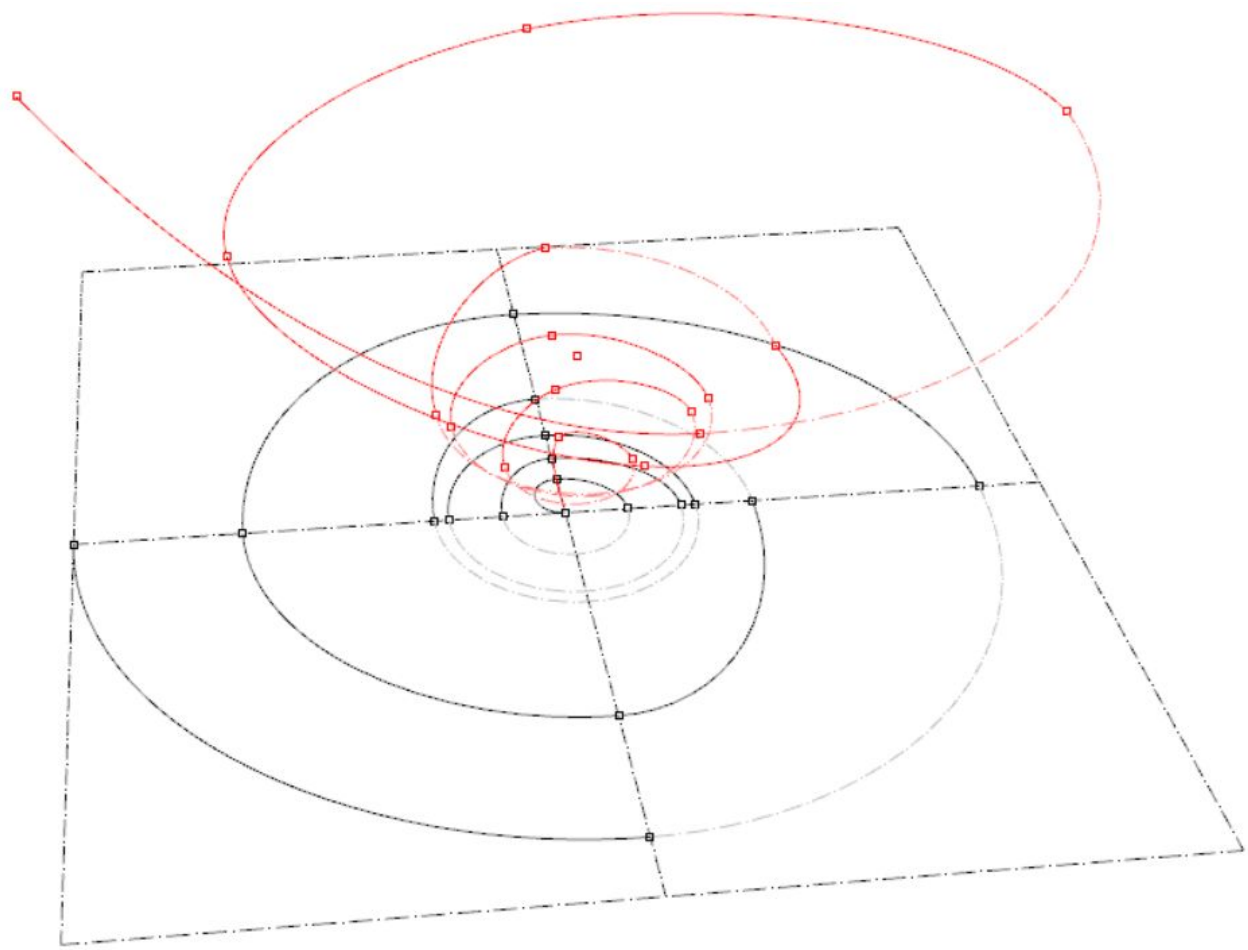

Figure D-1: 3D design signature example

STEPPED DESIGN SIGNATURES

Stepped design signatures, such as the example shown in Figure A-2, are yet another development on design signatures. Similarly mapped on a polar coordinate axis, we indicate time elapsed within each 'D' category by *stepping*, or increasing in *r*. Interestingly, this version was highly intuitive to some but persistently unclear to others. The team eventually decided to select a universally understood method of representing time elapsed (the stacked bar chart presented in Figures 8 to 12).

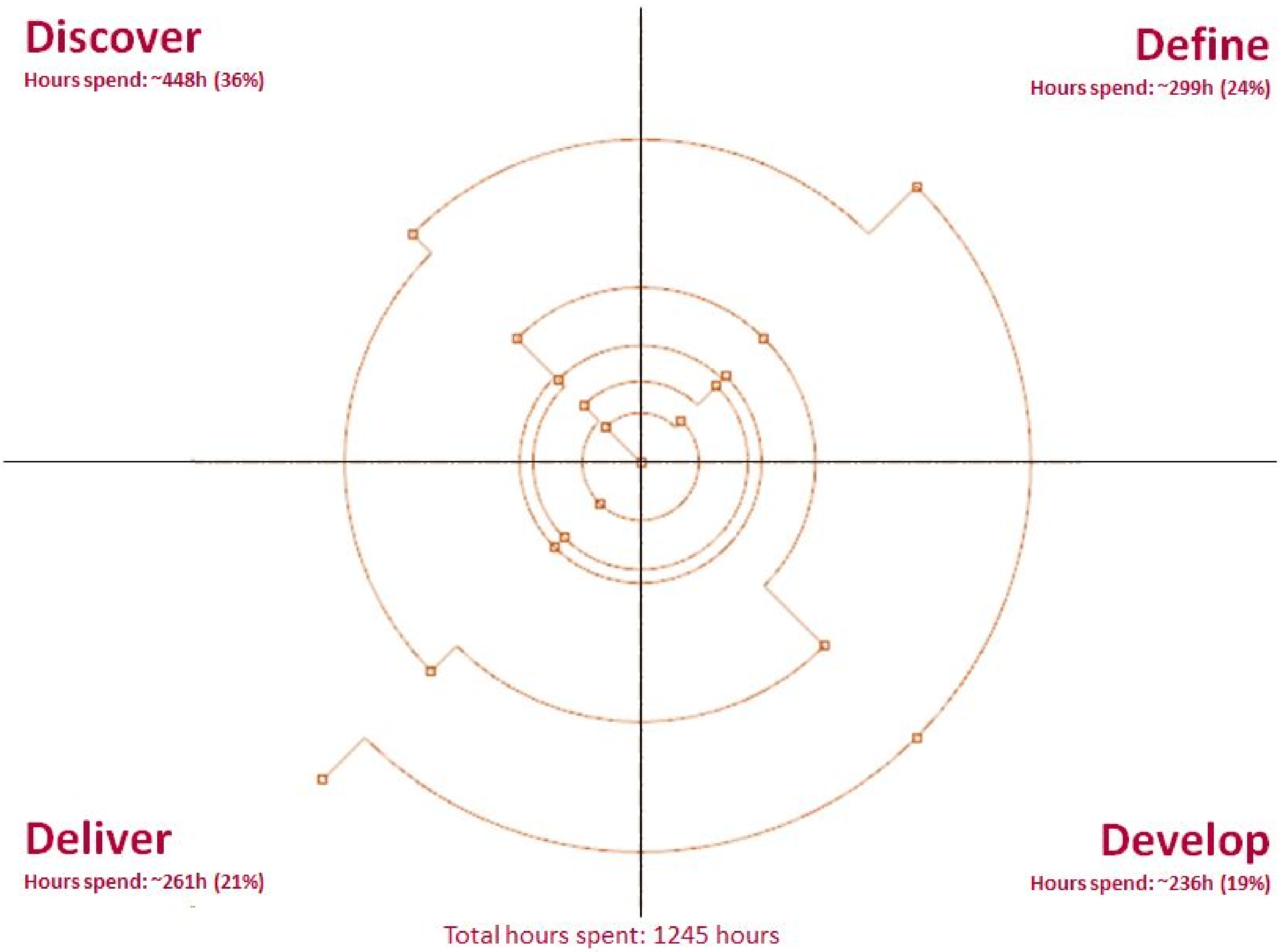

Figure D-2: Stepped design signature example

BOUNCING BALL MODEL

The *bouncing ball* models shown in Figure A-3 is retained in this paper for its simplicity and efficiency in conveying information about design processes. In this model, cartesian coordinates are used. The x-axis is a linear series that groups design activities together based on their 'D' category, while the independent axis denotes the four 'D' categories - Discover, Define, Develop, and Deliver. The size of each mark indicates the percentage of time spent within that category. This model provides the reader with an intuitive sense of total time elapsed within each 'D' category, as well as with oscillations between categories, but does not do a good job conveying iterations, or *loops*.

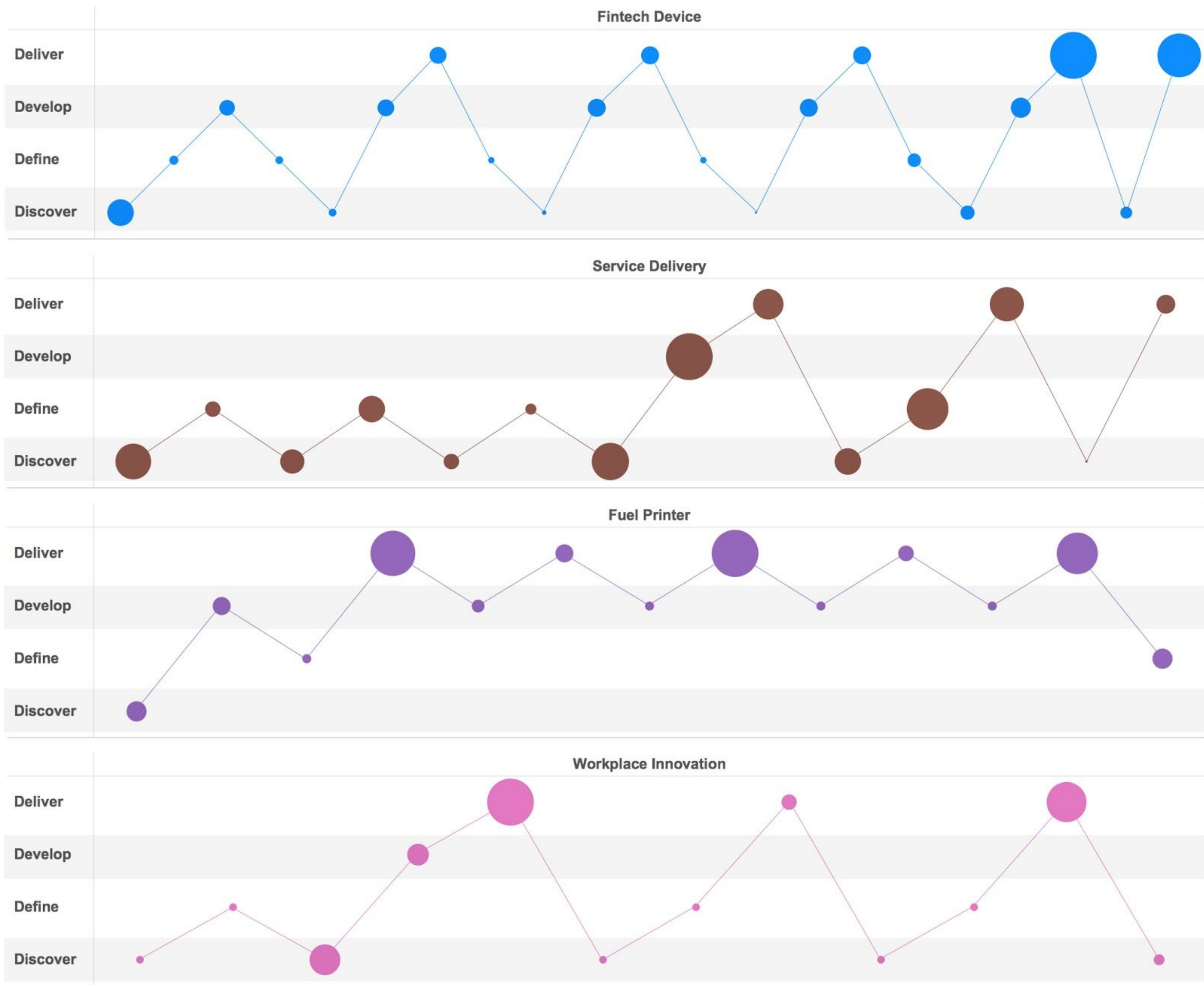

Figure A-3: Bouncing Ball Model