Background – Anant Chawla

Education

- B.S. in Mechanical Engg – Thapar University, India (May 2015)
- M.S. in Mechanical Engg – Clemson University, SC (May 2018)
- Study Abroad at NTU, Singapore (Aug – Dec 2017)
- Joined CEDAR in May 2017

Projects

- BMW Vehicle Assembly Center
- Continuum Robot Modeling
  - A. Chawla, C. Frazelle and I. D. Walker, "A Comparison of Constant Curvature Forward Kinematics for Multisection Continuum Manipulators," *IEEE International Conference on Robotic Computing (IRC)*, Laguna Hills, CA, 2018.

Submitted Paper

- A. Chawla and J. D. Summers, “Function Ordering within Morphological Charts: An Experimental Study,” in *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2018.

Effect of Functional Ordering on Morphological Chart Exploration

Anant Chawla

Committee Chair:

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Committee Members:

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CEDAR
CLEMSON ENGINEERING DESIGN APPLICATIONS AND RESEARCH

CLEMSON UNIVERSITY

Outline

- Introduction to Morph Charts
- Research Question & Hypothesis
- Experimental Procedure
- Analysis & Results
- Conclusions

Introduction to Morph Charts

What are Morph Charts?

- Tool used to systematically explore the design solution space (Pahl & Beitz, 2007)
- Consists of functions and solution means to achieve each function
- Combining one means for each functions produces an integrated design concept

Functions	Means		
1. Store Filling	1. Multi-serving package	2. Bulk filled hopper	3. Single serving package
2. Position Tortilla	1. Physical Stop	2. Visual Marker	3. Work on top of a stack of tortillas
3. Fill Tortilla	1. Pour filling onto tortilla	2. Spoon filling onto tortilla	3. Extrude filling through tube
4. Fold Burrito	1. Spatula lifts edges	2. Roll into tube	3. Punch through opening in table
5. Dispense Burrito	1. Gravity	2. Conveyor belt	3. Mechanical hand

Sample Morph Chart – Automatic Burrito Folding Machine

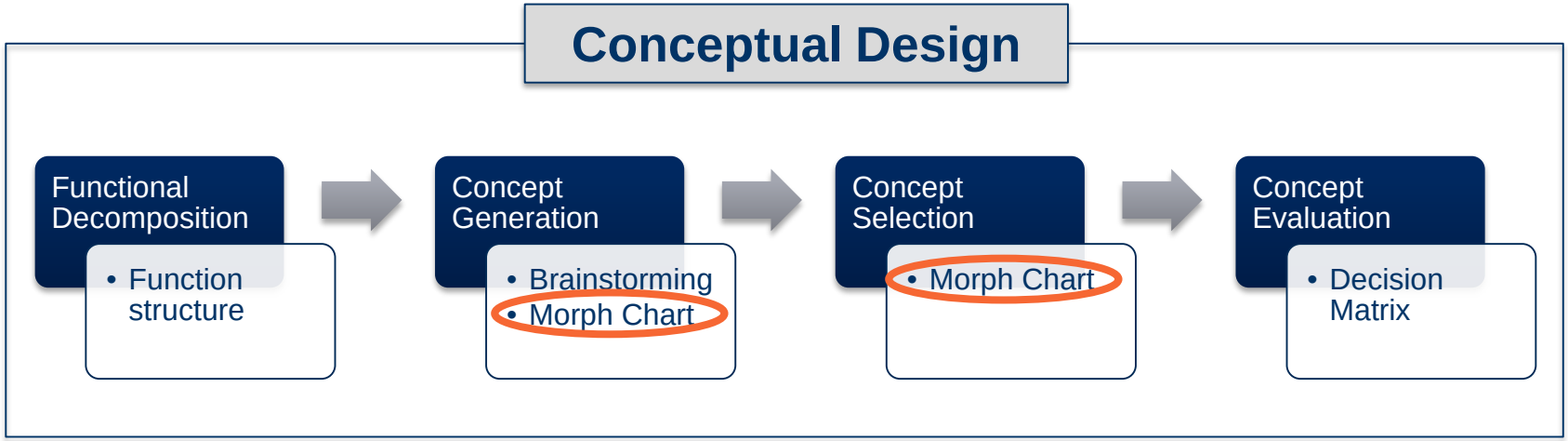
Selected Concepts:

F1M2	F1M3
F2M1	F2M1
F3M1	F3M2
F4M1	F4M1
F5M1	F5M3

Introduction to Morph Charts

Where are Morph Charts used?

- Morph charts are used in the Conceptual Design phase
- Support concept generation and concept selection activities (Shah, 1998)



How to use Morph Charts?

- List down functions and means at same level of detail (George, 2013)
- Discard infeasible means and incompatible combinations
- Generate integrated design concepts

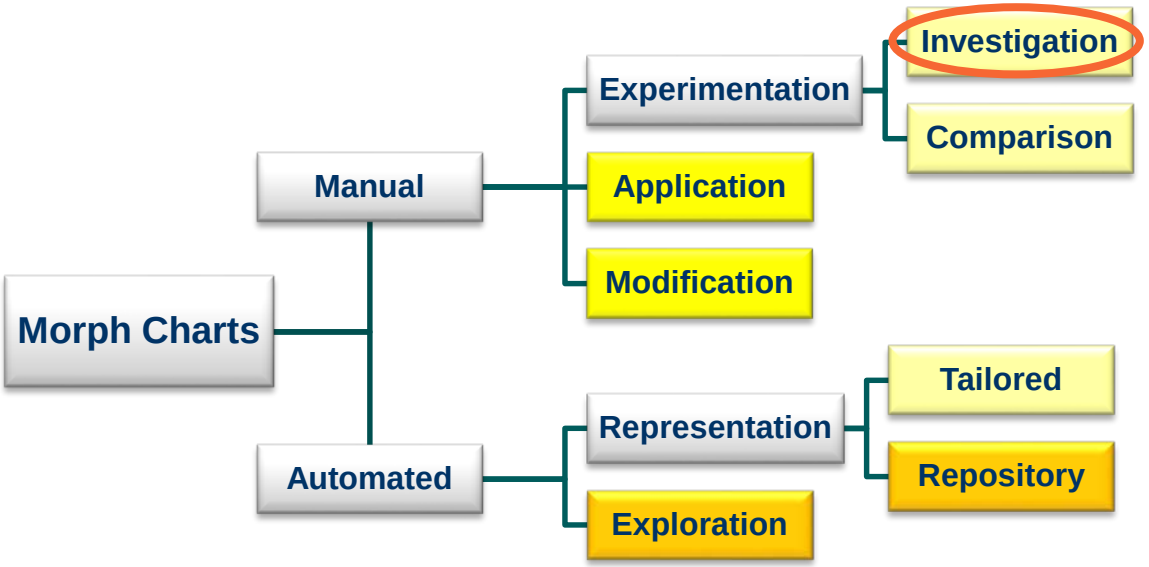
Motivation & Literature Review

Morph Chart Literature Map

- Widely recognized tool in engineering design applications and research
- Research into two broad categories: Manual and Automated
- Past CEDAR research: Investigation (Smith, 2012; Richardson, 2011), Modification (George, 2013; Teegavarapu 2009), Exploration (Tiwari, 2009)
- Current research falls under sub-category: Investigation (Experimentation)

Why study Morph Charts?

- To develop guidelines and recommendations
- To aid the creation of a computational support tool (Smith, 2012; Richardson, 2011)
- Multidisciplinary decision-making tool (Ritchey, 2005; Zeiler, 2013; Gogu, 2005; Johansen, 2018; Williams, 2013; de Fatima, 2017; Kannengiesser, 2013; Mansor, 2014)



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Research Question & Hypothesis

Research Question

How does the location of a function in a morph chart affect the selection of means associated with that function?

Hypothesis

Designers tend to focus relatively more on initial columns of the morph chart, irrespective of functional order.

Functions	Means		
F_1	$M_{1.1}$	$M_{1.2}$	$M_{1.3}$
F_2	$M_{2.1}$	$M_{2.2}$	$M_{2.3}$
F_3	$M_{3.1}$	$M_{3.2}$	$M_{3.3}$
F_4	$M_{4.1}$	$M_{4.2}$	$M_{4.3}$

Reverse

Functions	Means		
F_4	$M_{4.1}$	$M_{4.2}$	$M_{4.3}$
F_3	$M_{3.1}$	$M_{3.2}$	$M_{3.3}$
F_2	$M_{2.1}$	$M_{2.2}$	$M_{2.3}$
F_1	$M_{1.1}$	$M_{1.2}$	$M_{1.3}$

How is the morph chart explored?

- Which means are selected? – **Coverage**
- How many times are they selected? – **Frequency**
- In what sequence are they selected? – **Sequence**

How does a change in functional order affect?

- **Coverage**
- **Frequency**
- **Sequence**

Outline

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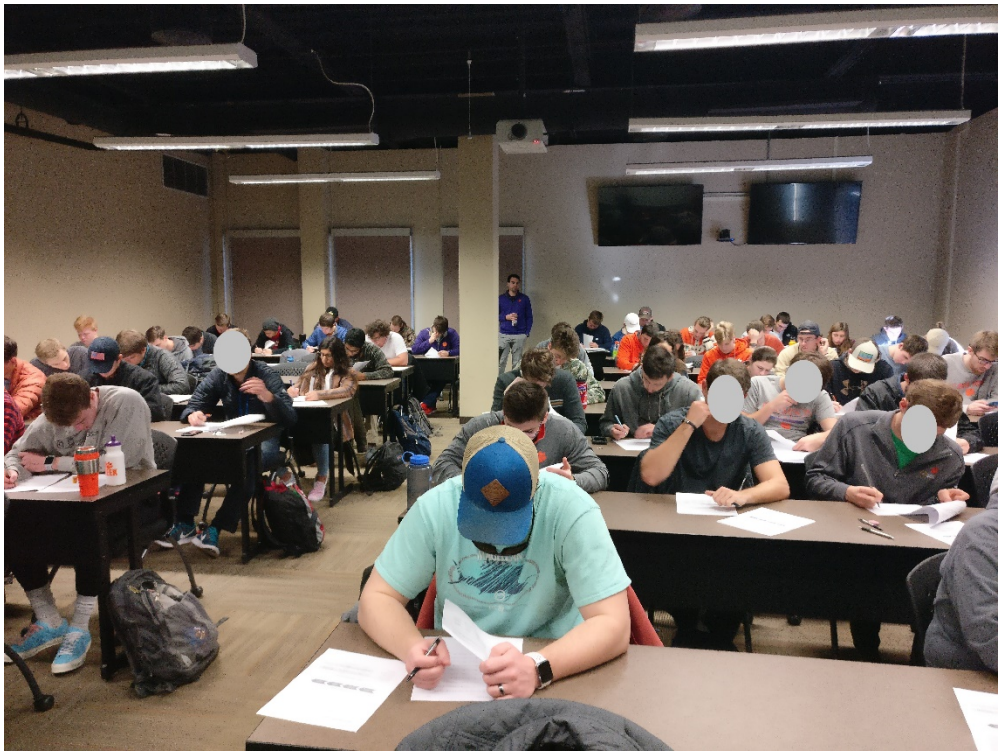
Experimental Procedure: Summary

Design Problems

- Two Design Problems (Patel, 2016)
  - Automatic Clothes Ironing Device
  - Automatic Recycling Sorter
- Five functional orders per problem



Participants

- 67 junior-level ME students
- Each student given two problems
- In-class activity

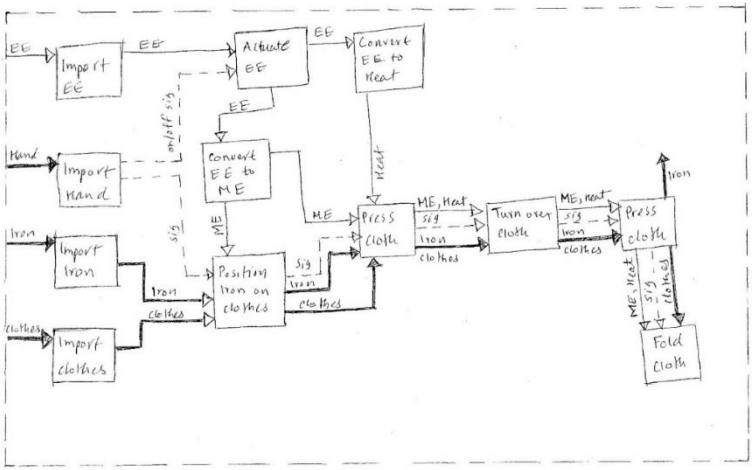
Experimental Handouts

- Prepopulated Morph Chart (of a particular functional order)
- Data Recording Sheet (space for 20 integrated design concepts)

Experimental Procedure: Morph Charts

Morph Chart: Functional Orders

- Most Imp to Least Imp Function ⟶ **Priority**
  - Counting the number of input-output flows in Function Structure
  - Assigning weights to flows (Energy – 9, Material – 3, Signal – 1)
- Least Imp to Most Imp Function ⟶ **Reverse Priority**
  - Reversing the Most-Imp-to-Least-Imp-Function
- Input to Output Function ⟶ **I/O**
  - Function Structure Input to Output
  - Top to Bottom convention
- Output to Input Function ⟶ **O/I**
  - Reversing the Input-to-Output-Function
- Random ⟶ **RND**
  - Deliberately structured to be RANDOM



Function Structure

Experimental Procedure: Design Problems

Problem 1 – Automatic Clothes Ironing Device

Given below is the Morphological Chart of an automatic clothes ironing device. The purpose of this device is to press wrinkled clothes as obtained from clothes dryer and fold them suitably for the garment type. The functions of this device are listed on the first column followed by the respective means. Your goal is to generate twenty promising concepts from the given morphological chart. Space is provided below for the mention of code for each function (F) and corresponding means (M), for example – F3M5, F2M1, etc. The generated concepts will be evaluated on usage cost, reliability, and ease of use.

Functions	Means				
1) Press Cloth	1) Linkage Mechanism	2) Cam & Follower	3) Belt or Chain Drive	4) Screw Mechanism	5) Rack & Pinion
2) Convert EE to ME	1) DC Motor	2) AC Synchronous Motor	3) AC Induction Motor	4) Linear Motor	5) Electro-Magnetic Switch
3) Turn Cloth	1) Cam & Follower	2) Linkage Mechanism	3) Gear Drive	4) Chain Drive	5) Belt Drive
4) Positioning	1) Linkage Mechanism	2) Cam & Follower	3) Belt or Chain Drive	4) Screw Mechanism	5) Gear Drive
5) Convert EE to Heat	1) Heating Element	2) Thermo-Electric Device	3) Heat Exchanger	4) Resistor	5) Magnetron (Microwave)
6) Fold Cloth	1) Linkage Mechanism	2) Cam & Follower	3) Belt Drive	4) Chain Drive	5) Gear Drive

Energy Conversion

Mechanical Motions

Experimental Procedure: Design Problems

Problem 2 – Automatic Recycling Sorter

Given below is the Morphological Chart of an automatic recycling machine for household use. The purpose of this device is to sort plastic bottles, glass containers, aluminum cans, and tin cans. The functions of this device are listed on the first column followed by the respective means. Your goal is to generate twenty promising concepts from the given morphological chart. Space is provided below for the mention of code for each function (F) and corresponding means (M), for example – F3M5, F2M1, etc. The generated concepts will be evaluated on usage cost, reliability, and ease of use.

Function	Means				
1) Convert EE to ME	1) DC Motor	2) AC Synchronous Motor	3) AC Induction Motor	4) Linear Motor	5) Electro-Magnetic Switch
2) Translate	1) Screw Mechanism	2) Rack & Pinion	3) Belt or Chain Drive	4) Linkage Mechanism	5) Cam & Follower
3) Convert EE To MagE	1) Electro-Magnet	2) Wire	3) Permanent Magnet	4) Ferro-magnet & coil	5) Super-conducting Magnet
4) Sort Solid	1) Machine Vision	2) 3D Scan & Weight	3) Acoustic	4) Infrared	5) Chemical Analysis
5) Guide	1) Linkage Mechanism	2) Gear Drive	3) Screw Mechanism	4) Cam Follower	5) Rack & Pinion
6) Compress Solid	1) Screw Mechanism	2) Linkage Mechanism	3) Belt or Chain Drive	4) Rack & Pinion	5) Spring

Energy Conversion
Mechanical Motions
Sorting

Experimental Procedure: Timeline

Introduction to Morph Charts	15 minutes
Morph Chart Practice Tutorial	
Pre-Sketching – Dream Home in Alaska	5 minutes
Problem #1 – Automatic Clothes Ironing Device	20 minutes
Pre-Sketching – Personal Yacht at U.S. Virgin Islands	5 minutes
Problem #2 – Automatic Recycling Sorter	20 minutes

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Analysis: Procedure

Number of concepts asked to generate: 20

Number of concepts analyzed: 10 (Oversaturation) (G. Smith, 2012)

Morph Chart size: 6x5 (3,125 integrated design concepts)

Discarded Samples

- Concepts: Incomplete or Irregular
- Participants: Means "6"
- Participants: Same means for 10 concepts across three or more functions (minimally explored)

Types of Analysis

- Frequency of Means Generation
  - Individual Means
  - Means Column
  - Effect of Functional Ordering
- Morph Chart Coverage
- Exploration Sequence
  - Row-wise
  - Column-wise

Analysis: Frequency

Frequency Position Matrix

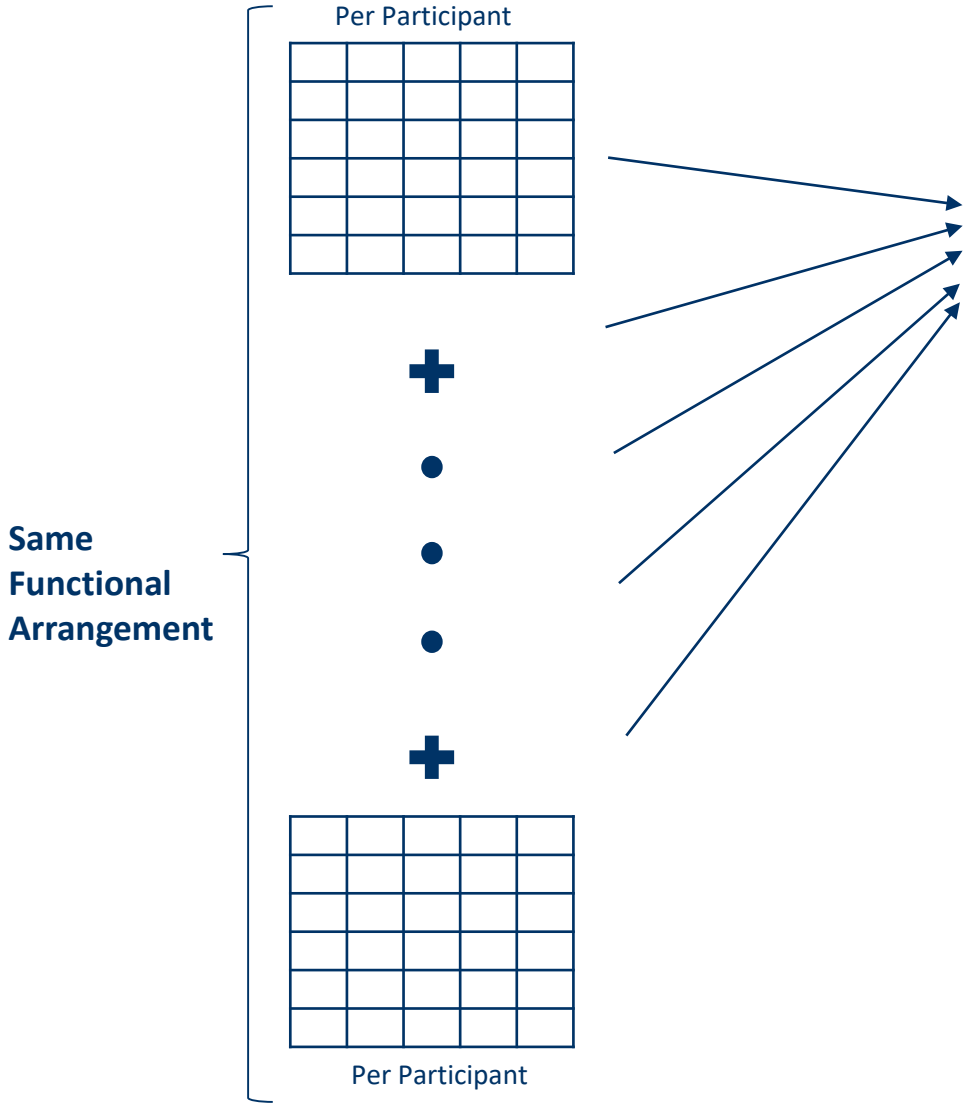
- Number of times a given means appeared in the set of generated concepts
- Sum of every row = number of integrated design concepts generated
- One *frequency position matrix* per participant
- F_x = Function X and M_y = Means Y

Functions	Means				
F1	$M_{1.1}$	$M_{1.2}$	$M_{1.3}$	$M_{1.4}$	$M_{1.5}$
F2	$M_{2.1}$	$M_{2.2}$	$M_{2.3}$	$M_{2.4}$	$M_{2.5}$
F3	$M_{3.1}$	$M_{3.2}$	$M_{3.3}$	$M_{3.4}$	$M_{3.5}$
F4	$M_{4.1}$	$M_{4.2}$	$M_{4.3}$	$M_{4.4}$	$M_{4.5}$
F5	$M_{5.1}$	$M_{5.2}$	$M_{5.3}$	$M_{5.4}$	$M_{5.5}$
F6	$M_{6.1}$	$M_{6.2}$	$M_{6.3}$	$M_{6.4}$	$M_{6.5}$

	M1	M2	M3	M4	M5	Σ
F1	2	0	1	0	0	3
F2	1	1	0	1	0	3
F3	1	1	0	0	1	3
F4	1	1	1	0	0	3
F5	2	1	0	0	0	3
F6	2	1	0	0	0	3

Sample Frequency Position Matrix
(for one participant)

Analysis: Frequency



Frequency Position Matrix
(per functional arrangement)

	M1	M2	M3	M4	M5	Σ
F1	36	23	22	13	16	**110**
F2	27	21	16	30	16	**110**
F3	52	15	13	9	21	**110**
F4	45	18	15	15	17	**110**
F5	29	23	23	12	23	**110**
F6	45	21	16	23	5	**110**

Reorder | **Normalize**

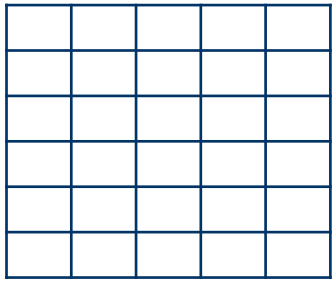
Normalized Frequency Position Matrix
(per functional arrangement)

	M1	M2	M3	M4	M5	Σ
F1	0.25	0.19	0.15	0.27	0.15	**1**
F2	0.41	0.16	0.14	0.14	0.15	**1**
F3	0.26	0.21	0.21	0.11	0.21	**1**
F4	0.33	0.21	0.20	0.12	0.15	**1**
F5	0.41	0.19	0.15	0.21	0.05	**1**
F6	0.47	0.14	0.12	0.08	0.19	**1**

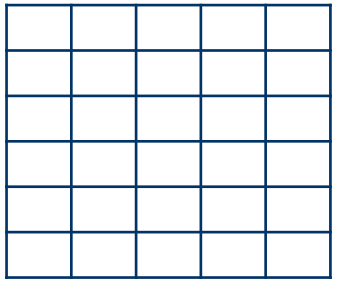
Analysis: Frequency

Individual Means

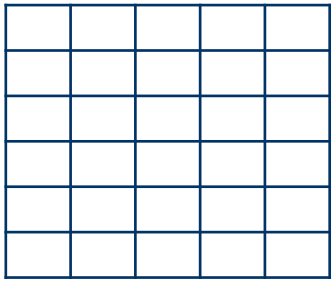
Priority



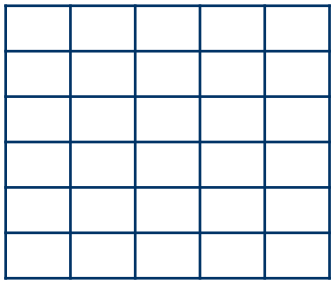
Reverse Priority



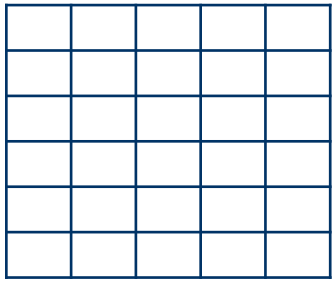
I/O



O/I



RND



Normalized Ranges	Gradient
0.00 to 0.05	
0.05 to 0.15	
0.15 to 0.25	
0.25 to 0.35	
0.35 to 0.45	
0.45+	

Results: Frequency

Individual Means – Problem 1

Priority

0.31				
0.28	0.31			
	0.29			
0.30				
0.33				
0.38				

Reverse Priority

0.32				
0.43				
	0.35			
0.31				
0.46				
0.45				

Normalized Ranges	Gradient
0.00 to 0.05	
0.05 to 0.15	
0.15 to 0.25	
0.25 to 0.35	
0.35 to 0.45	
0.45+	

I/O

	0.34			
0.40				
	0.42	0.25		
0.34		0.25		
0.43				
0.52				

O/I

0.26				
0.39				
	0.30			
0.30		0.26		
0.35				
0.29	0.25			

RND

0.41				
0.26				
0.33				
0.41				
0.47				

Results: Frequency

Individual Means – Problem 2

Priority

0.31	0.27			
0.30				
0.28				
			0.31	
0.34				
0.34				

Reverse Priority

0.35	0.38			
0.38				
0.38				
0.30		0.25		
0.28				
0.35				

I/O

			0.29	
0.35				
0.47				
		0.42		
0.30				
0.57				

O/I

0.31		0.28		
0.38				
0.25				0.25
		0.26		
	0.37			
0.32				

RND

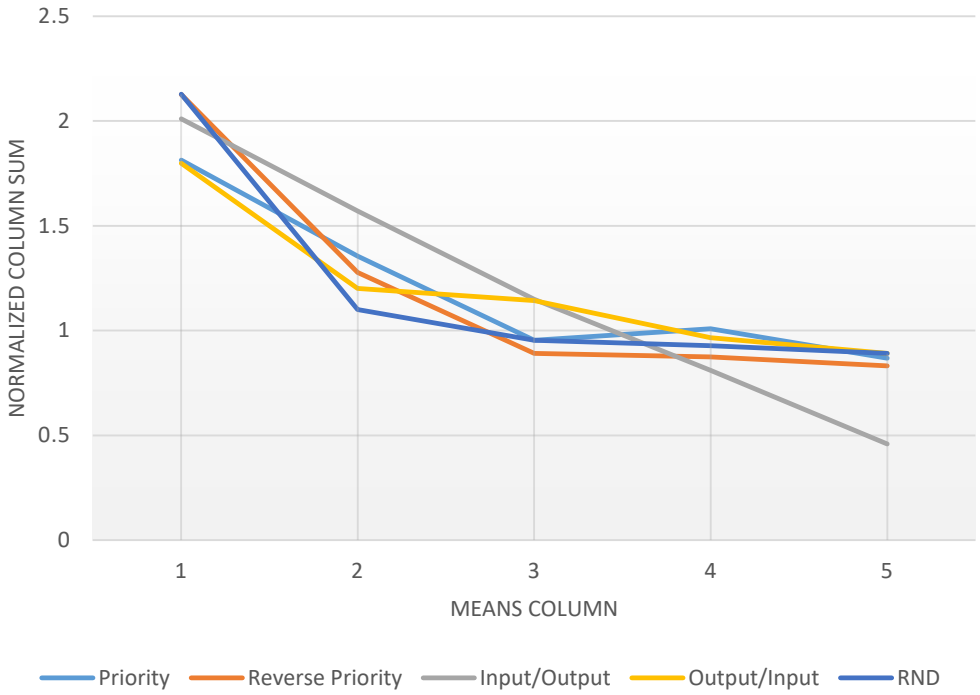
			0.31	
0.35				
0.40		0.26		
	0.31	0.33		
0.32				0.31
0.43				

- High gradient values (0.35+) in Column 1 & 2
- Exploration Uniformity in Priority and O/I
- Lends support to hypothesis

Results: Frequency

Means Column

- Column-wise means selection frequency
- Normalized *frequency position matrix* is summed along columns



- Decreasing selection frequency from left to right

- Lends support to hypothesis

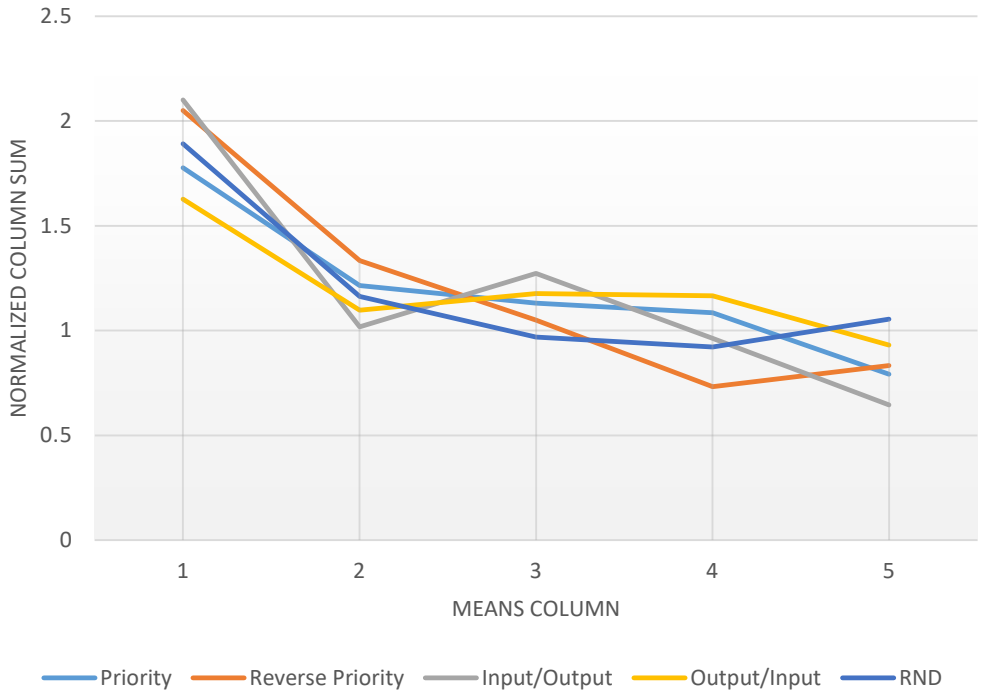
- All monotonically decreasing except one

Problem 1 – Means Column Selection Frequency

Results: Frequency

Means Column

- Column-wise means selection frequency
- Normalized *frequency position matrix* is summed along columns



- Decreasing selection frequency from left to right

- Lends support to hypothesis

- Only one monotonically decreasing (effect of problem type?)

Problem 2 – Means Column Selection Frequency

Analysis: Coverage

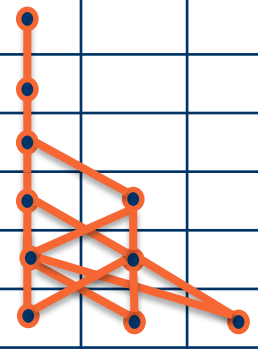
Morph Chart Coverage

- Number of unique means explored by participant to develop design concepts
- Includes means that were explicitly eliminated in the chart
- Indicates degree of design space exploration

Minimum Coverage: 10 (fewest means used to develop 10 unique design concepts)

Maximum Coverage: 30 (morph chart size)

	M1	M2	M3	M4	M5
F1					
F2					
F3					
F4					
F5					
F6					

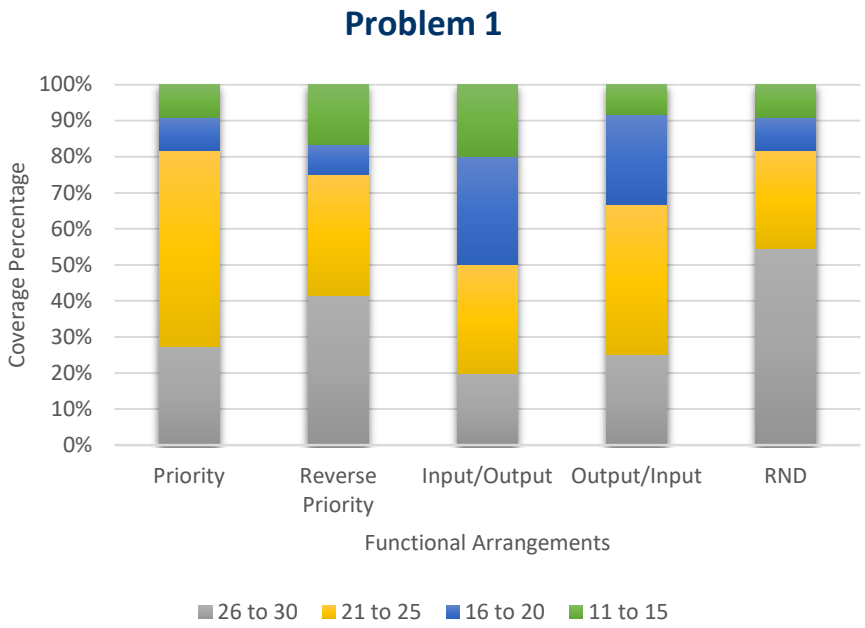


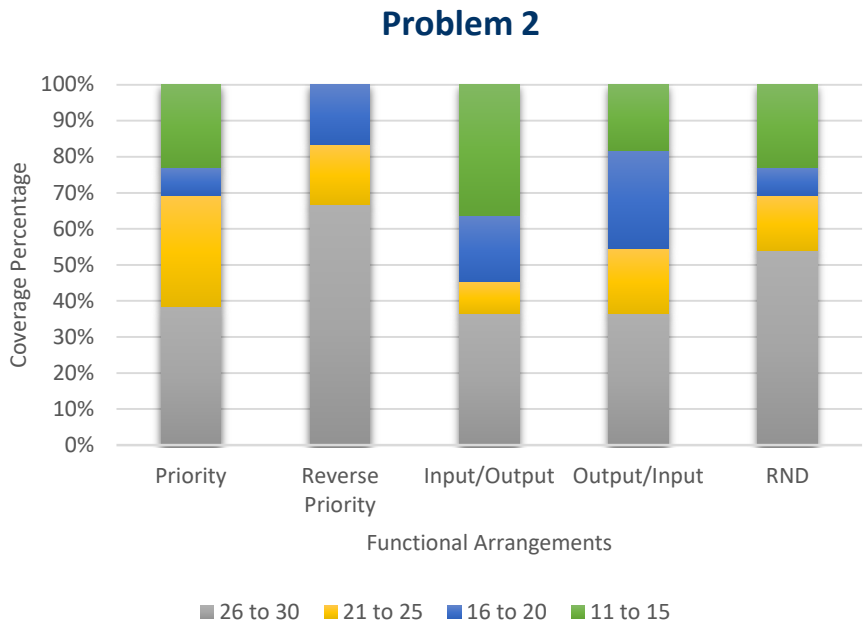
Concept 1	F1M1-F2M1-F3M1-F4M1-F5M1-F6M1
Concept 2	F1M1-F2M1-F3M1-F4M1-F5M1-F6M2
Concept 3	F1M1-F2M1-F3M1-F4M1-F5M1-F6M3
Concept 4	F1M1-F2M1-F3M1-F4M1-F5M2-F6M1
Concept 5	F1M1-F2M1-F3M1-F4M1-F5M2-F6M2
Concept 6	F1M1-F2M1-F3M1-F4M1-F5M2-F6M3
Concept 7	F1M1-F2M1-F3M1-F4M2-F5M1-F6M1
Concept 8	F1M1-F2M1-F3M1-F4M2-F5M1-F6M2
Concept 9	F1M1-F2M1-F3M1-F4M2-F5M1-F6M3
Concept 10	F1M1-F2M1-F3M1-F4M2-F5M2-F6M1

Minimum Coverage Morph Chart

Results: Coverage

Morph Chart Coverage





- Participant values grouped into four ranges
- High coverage is 21 to 30 (color grey and yellow)
- Low coverage is 11 to 20 (color green and blue)

Problem 1 – Priority & RND > Reverse Priority > O/I > I/O

Problem 2 – Reverse Priority > Priority & RND > O/I > I/O

Exploration Sequence

- Step-by-step navigation of the morph chart
- Data recording sheet requests function code and means code
- Exploration Graphs
  - Row-wise (F1-F2-F3-F4-F5-F6, F3-F5-F1-F6-F2-F4, …)
  - Column-wise (*Exploration Matrix*)

Data Recording Sheet

Concept 2:

F____ M____ F____ M____ F____ M____ F____ M____

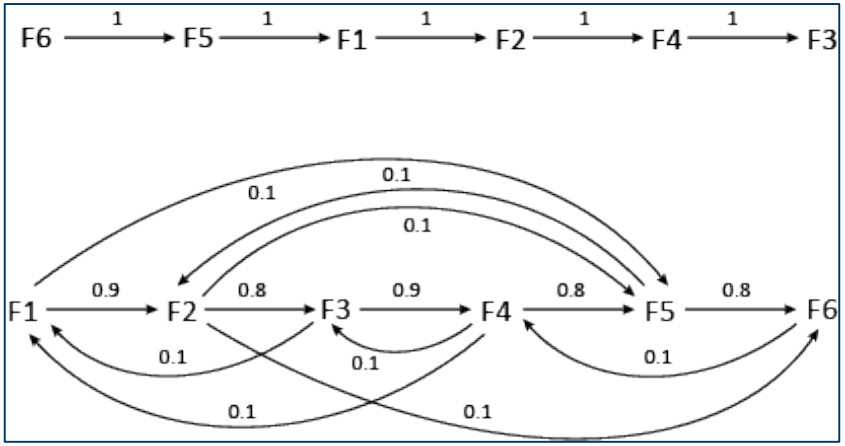
Concept 3:

F____ M____ F____ M____ F____ M____ F____ M____

Results: Exploration Sequence

Row-wise

Problem 1		Problem 2	
Functional Order	**Participant Alterations**	**Functional Order**	**Participant Alterations**
Priority	0 (of 13)	Priority	6 (of 15)
Reverse Priority	1 (of 13)	Reverse Priority	5 (of 10)
Input/Output	1 (of 13)	Input/Output	0 (of 15)
Output/Input	7 (of 15)	Output/Input	1 (of 13)
RND	5 (of 13)	RND	1 (of 14)



Function-wise Exploration Graphs

- Overall low number of row-wise alterations
- Only I/O arrangement did not undergo high alterations

Analysis: Exploration Sequence

Column-wise - Exploration Matrix

- Number of times the participant navigates from one column to another
- Row number indicates the start and column number indicates the follow-up
- Example: from C2 to C1: 37 times, from C2 to C2 itself: 36 times, from C2 to C3: 23 times, from C2 to C4: 13 times, and from C2 to C5: 17 times

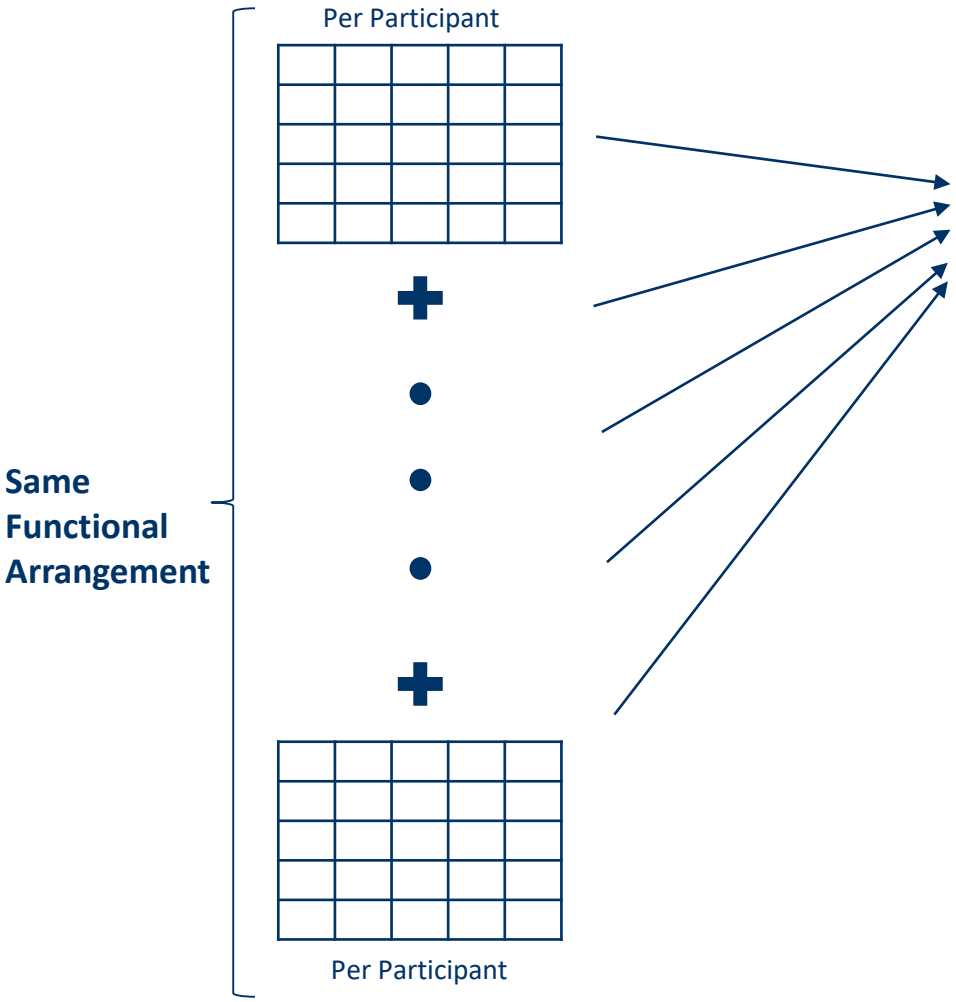
Follow

Start

	C1	C2	C3	C4	C5	Σ
C1	60	35	15	20	23	**153**
C2	37	36	23	13	17	**126**
C3	19	21	18	19	10	**87**
C4	28	19	21	19	10	**97**
C5	17	12	10	16	17	**72**
Σ	**161**	**123**	**87**	**87**	**77**	

Sample Exploration Matrix (for each participant)

Analysis: Exploration Sequence



Exploration Matrix
(per functional arrangement)

	C1	C2	C3	C4	C5	Σ
C1	60	35	15	20	23	**153**
C2	37	36	23	13	17	**126**
C3	19	21	18	19	10	**87**
C4	28	19	21	19	10	**97**
C5	17	12	10	16	17	**72**
Σ	**161**	**123**	**87**	**87**	**77**	

Normalize

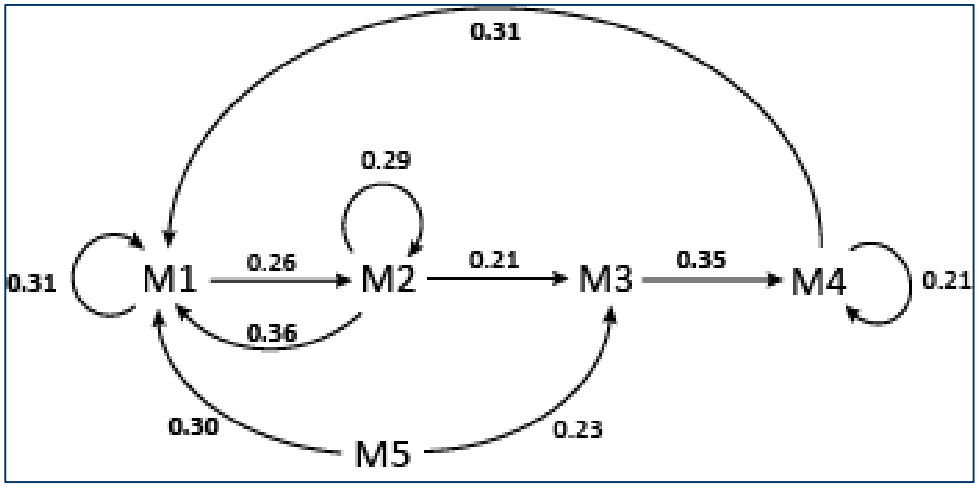
Normalized Exploration Matrix
(per functional arrangement)

Start

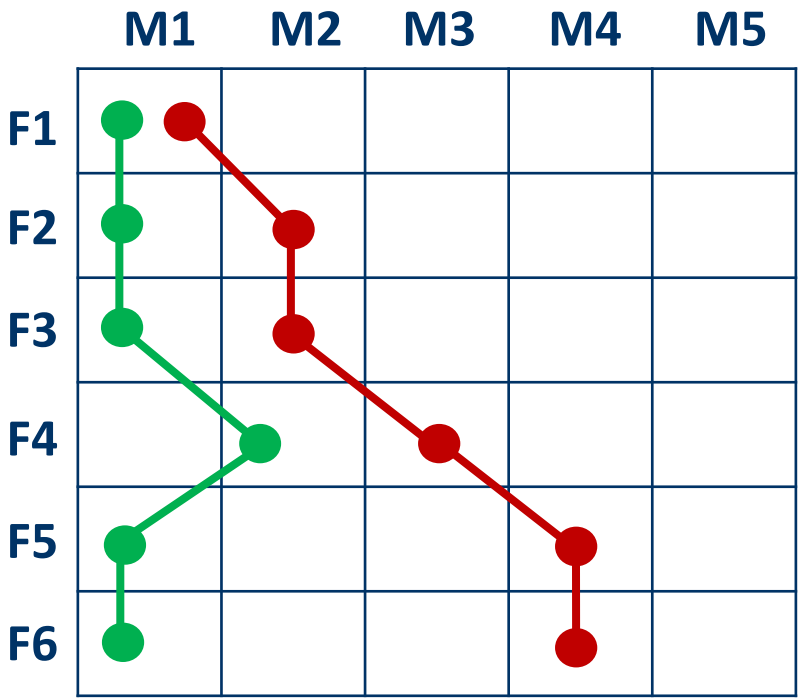
	C1	C2	C3	C4	C5
C1	0.39	0.23	0.10	0.13	0.15
C2	0.29	0.29	0.18	0.10	0.13
C3	0.22	0.24	0.21	0.22	0.11
C4	0.29	0.20	0.22	0.20	0.10
C5	0.24	0.17	0.14	0.22	0.24

Normalized exploration matrix screened for values greater than 0.2

Results – Exploration Sequence



Problem #2 Priority Column-wise Exploration Graph



- High inbound on M1 and M2
- High inbound values on M1

Outline

- Introduction to Morph Charts
- Research Question & Hypothesis
- Experimental Procedure
- Analysis & Results
- Conclusions

Conclusions

Observations

- High exploration of initial morph chart columns
  - Frequency of Individual Means
  - Frequency of Means Column
  - Column-wise Exploration Sequence
- Functional Ordering does not influence the overall exploration pattern, however, individual differences can be found.
- Exploration sequence is different for all functional orders

Hypothesis ☑

Designers tend to focus relatively more on initial columns of the morph chart, irrespective of functional order.

Conclusions

Guidelines

- If we want designers to explore the **morph chart uniformly**, arrange the morph chart to
  - Priority functional arrangement
  - Output-to-Input functional arrangement
- If we want designers to explore the **morph chart fully**, arrange the morph chart to
  - Priority functional arrangement
  - Reverse Priority functional arrangement
  - Random functional arrangement

Future Work

- How does the order of listing means for any given function in a morphological chart influence concept exploration?
  - Complementary to this research
  - Effect of Means Ordering
- How does the type of design problem influence concept exploration using morphological charts?
  - Observation followed from current research
  - Effect of problem type
- How does the representation of means in a morphological chart – textual, graphical or hybrid, impact the generated concepts?
  - Lack of guidelines in literature
  - Effect of means representation

THANK YOU

Questions?

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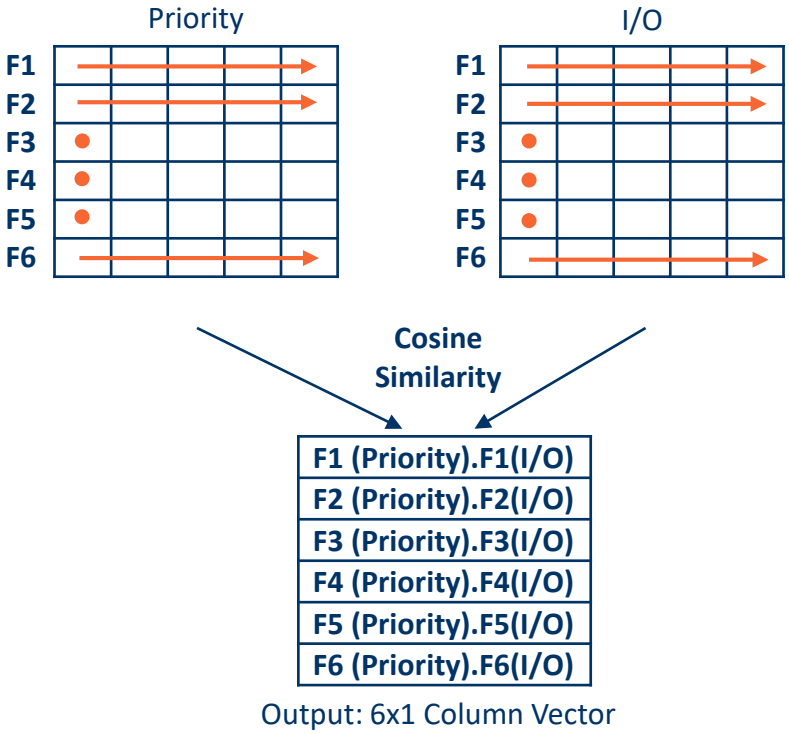
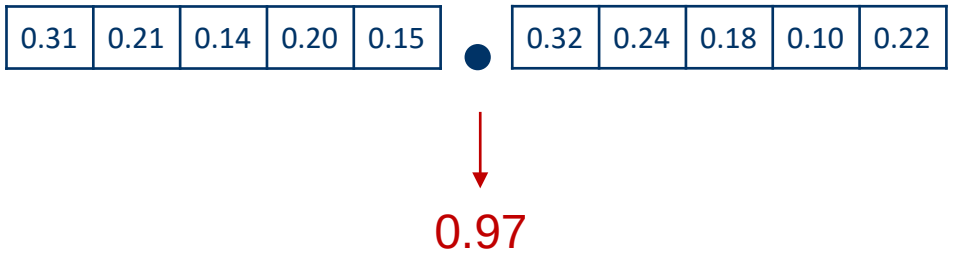
Backup Slides

Analysis: Frequency

Effect of Functional Ordering

- Obtain cosine similarity between two functional arrangements (normalized *frequency position matrices*) by treating every row (function) as a vector
- Obtain the average similarity for each function between all five different functional arrangements

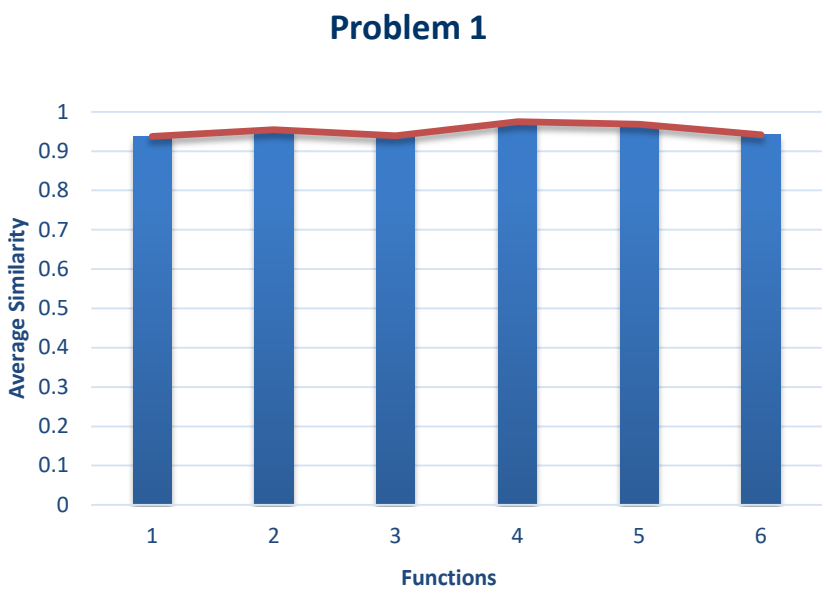


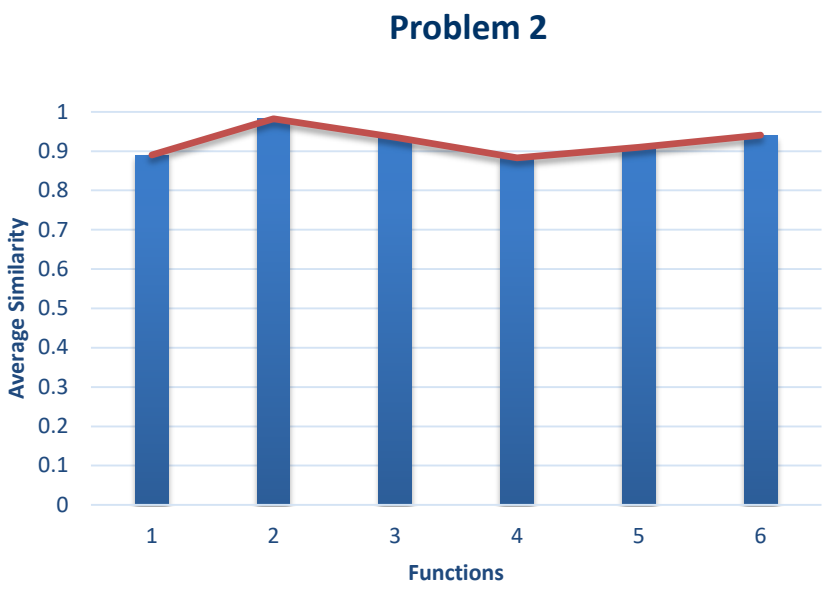


	Priority	Reverse Priority	I/O	O/I	RND
Priority		☑	☑	☑	☑
Reverse Priority			☑	☑	☑
I/O				☑	☑
O/I					☑
RND					

Results: Frequency

Effect of Functional Ordering





- High similarity, no noticeable effect of function ordering
- Lends support to hypothesis
- Less similarity in problem 2 comparatively (effect of problem type?)

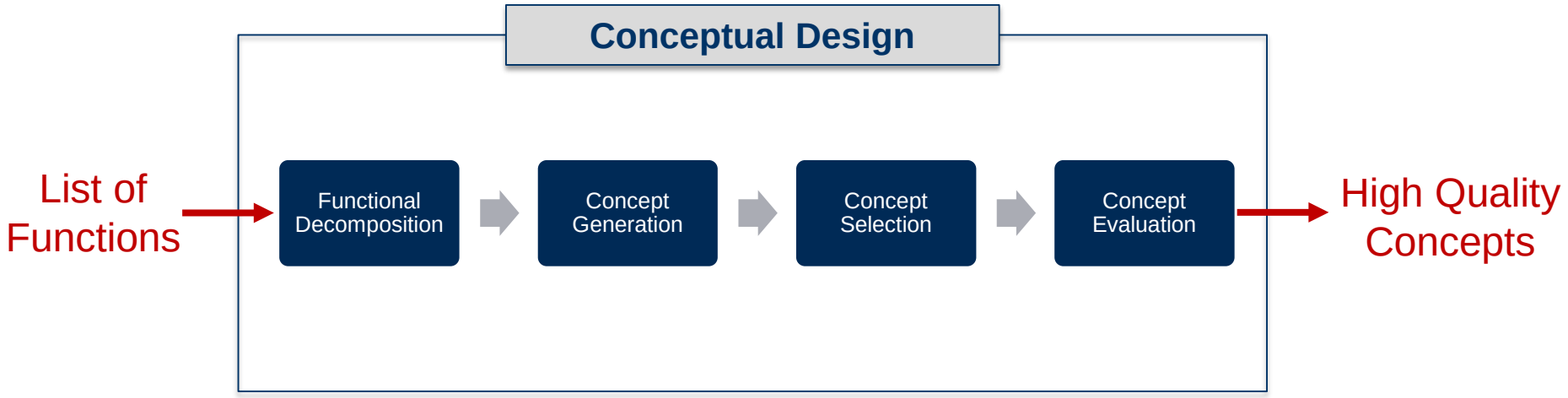
Results: Exploration Sequence

Column-wise

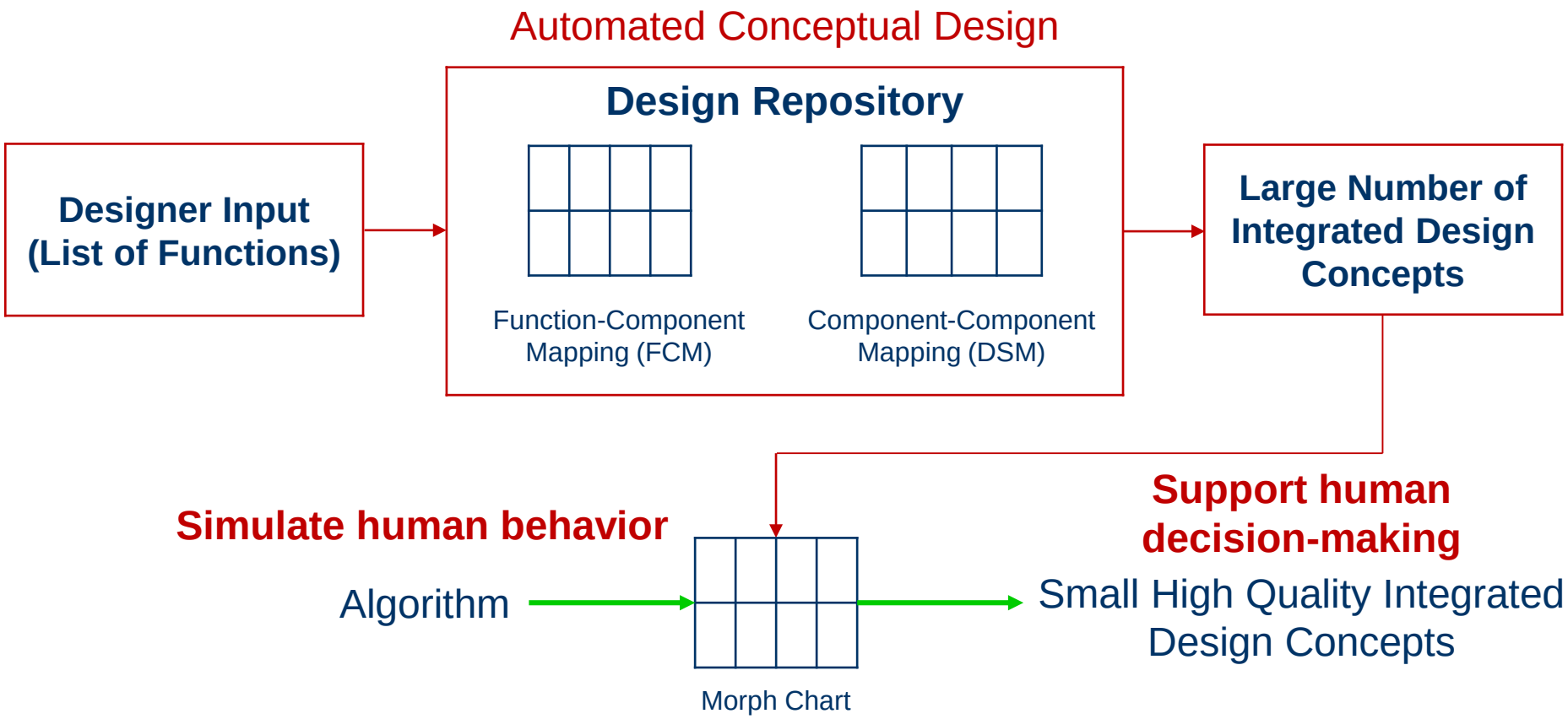
- Normalized *exploration matrix* screened for values greater than 0.2
- Values greater than 0.3 emphasized in bold
- Followed convention (to make graphs as similar as possible):
  - Screened values analyzed one row at a time from top to bottom
  - Location of identified values conveys the exploration sequence
  - **Low** means column number to **high** means column number (e.g. M1 to M2): **Left to Right Arrow**
  - **High** means column number to **low** means column number (e.g. M3 to M2): **Bottom to Top Arrow**
  - If multiple sequences, arrows placed at an angle
  - Starting point for each graph is M1

	C1	C2	C3	C4	C5
C1	-	-	-	-	-
C2	-	-	-	-	-
C3	-	-	-	-	-
C4	-	-	-	-	-
C5	-	-	-	-	-

Computational Support Tool



Computational Support Tool



Data Recording Sheet

Concept 1:

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

Concept 2:

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

Concept 3:

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

Concept 4:

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

Concept 5:

F____ M____ F____ M____ F____ M____ F____ M____ F____ M____ F____ M____

Discarded Samples – Excel Entries

Category 1

	F1	F2	F3	F4	F5	F6
Concept 1	3	1	4	3	1	1
Concept 2	4	3	3	2	2	3
Concept 3	3	2	2	1	4	1
Concept 4	2	5	4	6	3	1
Concept 5	1	4	5	6	5	2
Concept 6	5	6	6	4	6	5
Concept 7	6	1	6	5	1	6
Concept 8	4	2	5	2	3	4
Concept 9	3	3	4	3	3	1
Concept 10	2	4	1	4	2	2

Category 3

	F1	F2	F3	F4	F5	F6
Concept 1	5	4	1	1	1	1
Concept 2	4	4	1	1	1	1
Concept 3	5	1	1	1	1	1
Concept 4	4	1	1	1	1	1
Concept 5	5	4	2	1	1	1
Concept 6	4	4	2	1	1	1
Concept 7	5	1	2	1	1	1
Concept 8	4	1	2	1	1	1
Concept 9	1	1	1	1	1	1
Concept 10	5	3	1	1	1	1

Category 2

	F1	F2	F3	F4	F5	F6
Concept 1	5	2	3	5	1	5
Concept 2	3	2	1	1	3	3
Concept 3	4	2	1	3	3	3
Concept 4	5	2	3	3	1	3
Concept 5	5	2	1	3	1	3
Concept 6	5	2	1	1	1	5
Concept 7	5	5	3	2	3	2
Concept 8	1	1	3	1	3	3
Concept 9	1	2	1	2	1	2
Concept 10	J	M	A	A	C	J

	F1	F2	F3	F4	F5	F6
Concept 1	1	3	5	1	1	1
Concept 2	2	2	2	2	4	3
Concept 3	4	1	2	4	5	4
Concept 4	4	4	3	4	4	3
Concept 5	1	1	2	4	4	3
Concept 6						
Concept 7						
Concept 8	4	3	2	1	1	1
Concept 9	1	1	5	3	3	1
Concept 10	5	1	5	3	3	2

Row-wise Functional Ordering

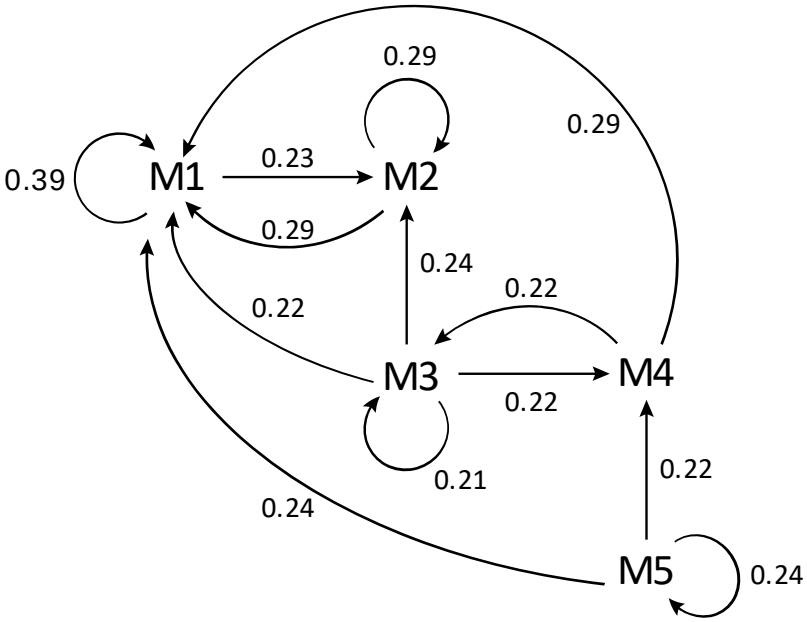
Please keep these criteria in mind when generating concepts for the given product.

Functions	Means				
1) Convert EE To MagE	1) Electro-Magnet	2) Wire	3) Permanent Magnet	4) Ferro-magnet & coil	5) Super-conducting Magnet
2) Guide	1) Linkage Mechanism	2) Gear Drive	3) Screw Mechanism	4) Cam Follower	5) Rack & Pinion
3) Translate	1) Screw Mechanism	2) Rack & Pinion	3) Belt or Chain Drive	4) Linkage Mechanism	5) Cam Follower
4) Convert EE to ME	1) DC Motor	2) AC Synchronous Motor	3) AC Induction Motor	4) Linear Motor	5) Electro-Magnetic Switch
5) Compress Solid	1) Screw Mechanism	2) Linkage Mechanism	3) Belt or Chain Drive	4) Rack & Pinion	5) Spring
6) Sort Solid	1) Machine Vision	2) 3D Scan & Weight	3) Acoustic	4) Infrared	5) Chemical Analysis

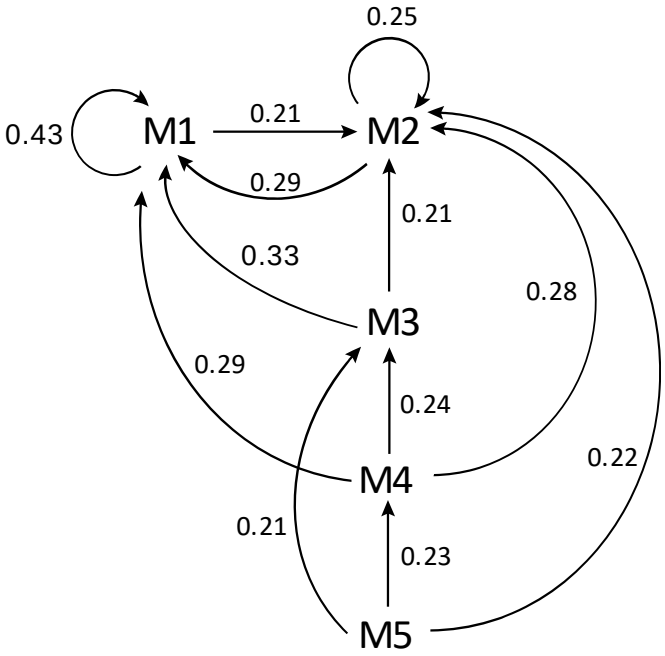
Figure 2 – Morphological Chart of an Automatic Recycling Machine

2 ⇒ 3 ⇒ 1 ⇒ 6 ⇒ 4 ⇒ 5

Column-wise Exploration Sequence

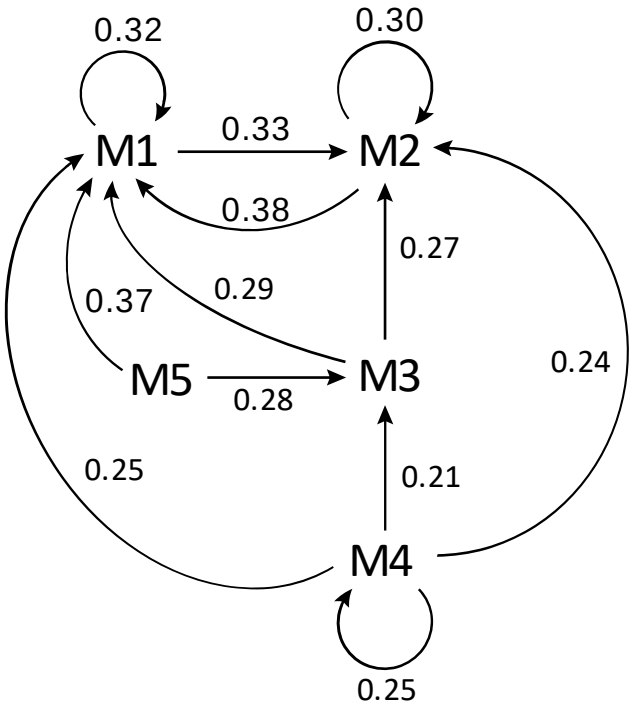


Problem #1 Priority Column-wise Exploration Graph

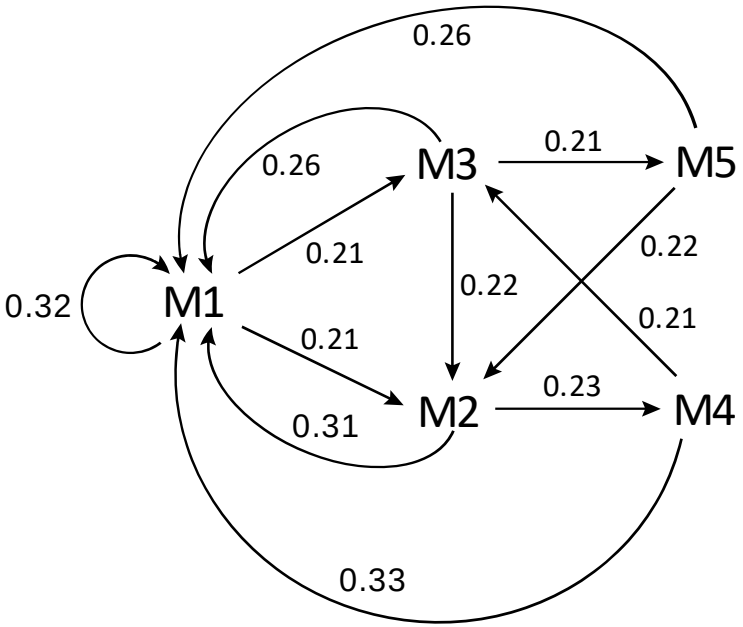


Problem #1 Reverse Priority Column-wise Exploration Graph

Column-wise Exploration Sequence

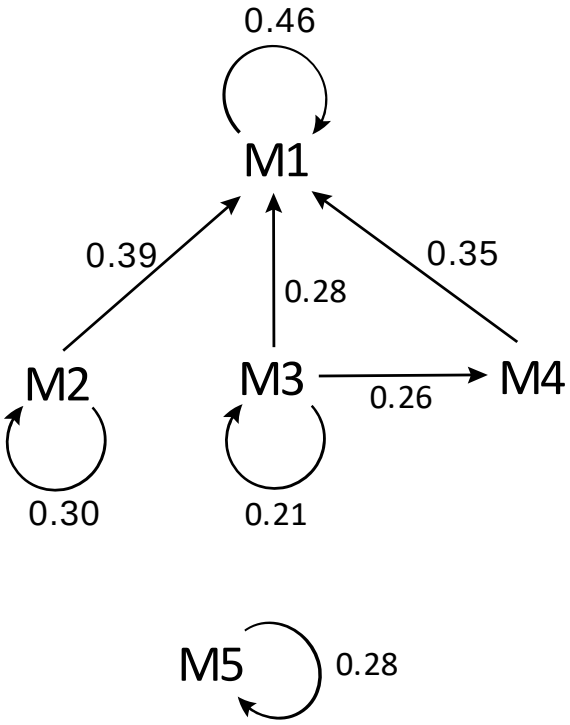


Problem #1 I/O Column-wise Exploration Graph

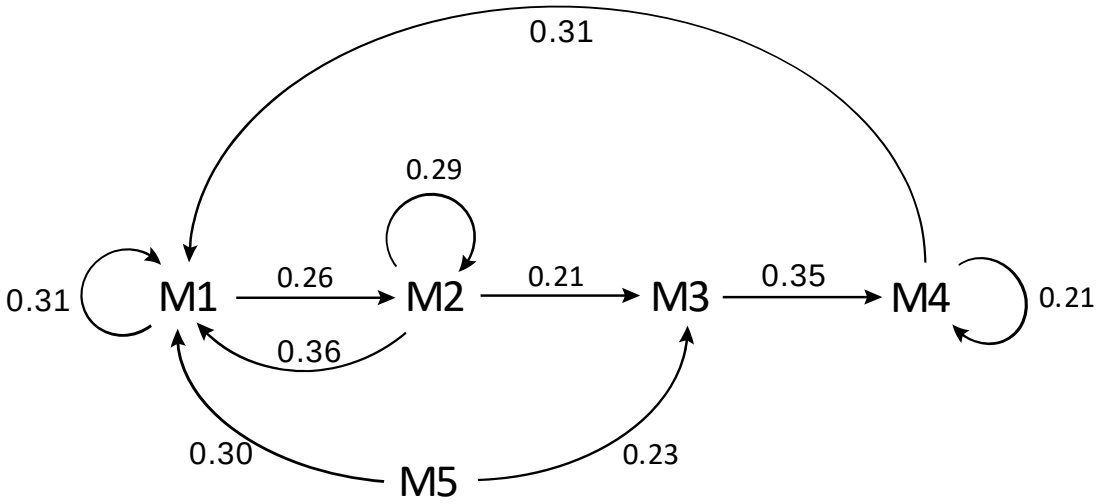


Problem #1 O/I Column-wise Exploration Graph

Column-wise Exploration Sequence

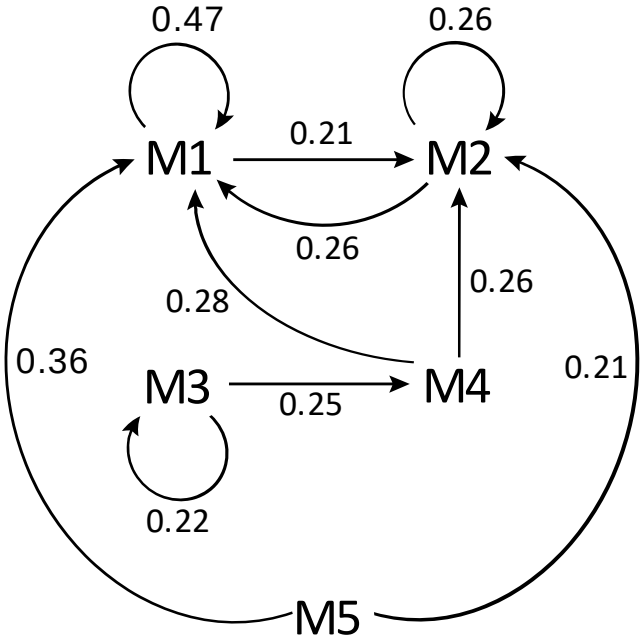


Problem #1 RND Column-wise Exploration Graph

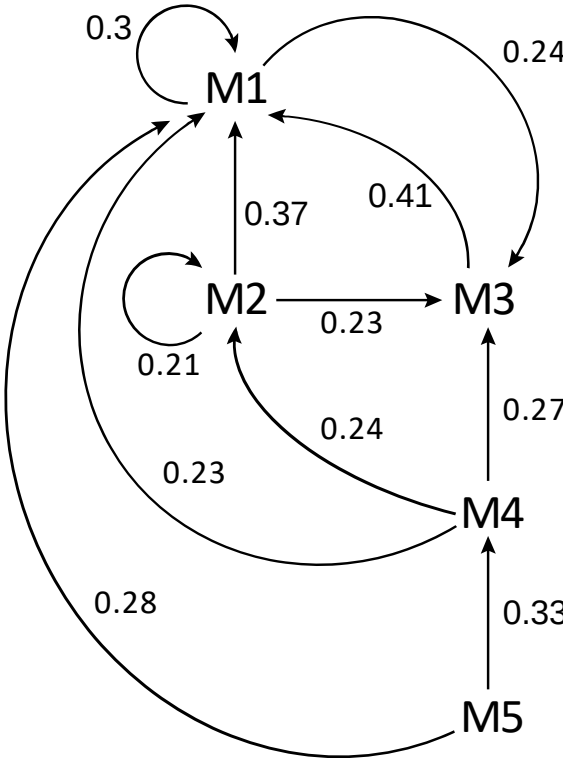


Problem #2 Priority Column-wise Exploration Graph

Column-wise Exploration Sequence

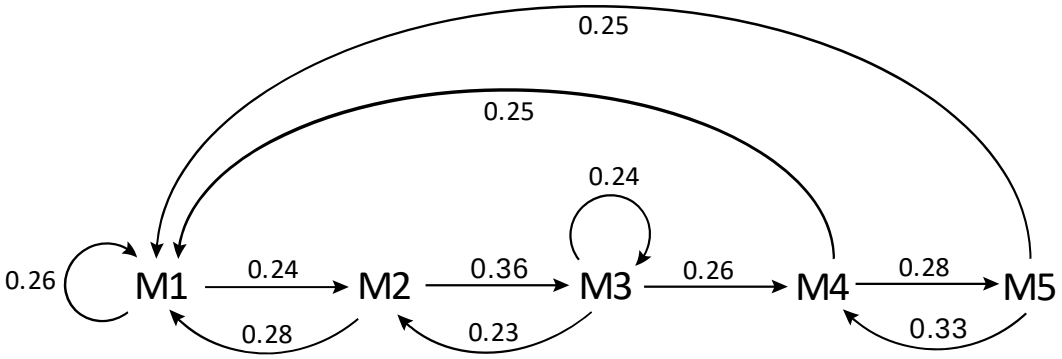


Problem #2 Reverse Priority Column-wise Exploration Graph

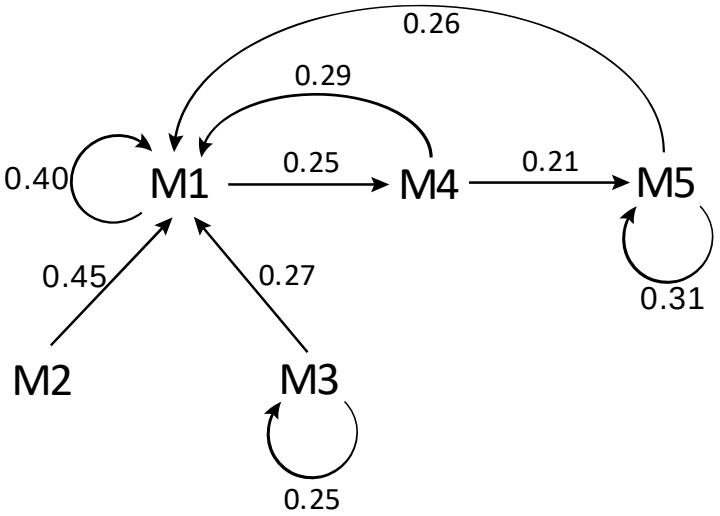


Problem #2 I/O Column-wise Exploration Graph

Column-wise Exploration Sequence



Problem #2 O/I Column-wise Exploration Graph



Problem #2 RND Column-wise Exploration Graph