Constructing Local Stories for Global Insight: Detecting Dominant Structure Forrester's Market Growth Model

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Abstract

Simulation reveals what the consequence of a feedback system is; however, it remains silent and mysterious about why. Identifying dominant structure to uncover why a system does what it does has been one of the central challenges in system dynamics modeling practices. This paper reports the application of pathway participation metrics in Forester's classic market growth model to identify the dominant feedback structure in the observed behavior under alternative assumptions. It shows that the results are consistent with Forrester's intuitive explanations. This paper offers some heuristic of understanding oscillatory systems.

Simulation reveals what the consequence of feedback structures is; however, it remains silent and mysterious about why. Identifying the dominant structure to uncover why a system does what it does has been one of the central challenges in system dynamics modeling practices. Formal methods for detecting dominant structure have been developed over the last five decades to support explanations of system behavior. Similar to traditional intuitive approach in model analysis, pathway participation method begins with the variable of interest and its observed behavior, tells local stories of partial structure and strive to arrive at explanation of global attributes of observed behavior. Eigenvalue elasticity approach begins with global system level stories and is challenged with connecting those stories to the observed behavior. The first section of this paper describes methods of explanation in oscillatory systems and the formal approaches that have been developed to support these explanations. The second part of the paper reports the application of pathway participation metrics in market growth model and contrasts the findings with Forrester's intuitive explanation.

Explaining Oscillation:

Oscillatory systems have been investigated from different perspectives. In the field of system dynamics, intuitive and simple explanation of oscillatory systems in terms of its feedback structure has been one of the main challenges. Graham (1977) investigates a wide range of questions related to the understanding of oscillation and outlines different approaches developed to explain cyclical behavior. He differentiate explanation based on "clearly identifying underlying structures necessary for oscillation" from description and strives to address the challenge of identifying a subset of the feedback structure, in a complex and relatively large systems, as the main driver of the cyclical behavior observed.

In system dynamics literature one can identify at least two distinct explanations for cyclical behavior in feedback models: Explanations based on (1) phases in oscillation (Senge et al, 1975; Graham, 1977), and (2) various attributes of cycles in oscillatory systems including periodicity, amplitude (Kampmann, 2009; Güneralp, 2006; Sterman, 2000; Forester 1982; Graham, 1977). Each explanation strives to answer different questions about the behavior observed in the simulation.

Figure 1 depicts the focus area for the two explanations. The phase-based explanations provide answers to the questions such as: Is the variable of interest increasing or decreasing as it goes through the cycles? And how fast? What is the partial structure that cause the changes observed in the variable of interest? The latter, explanation of observed cycles, provides answers to the questions such as: what is the periodicity in the cycles? Do cycles damp or expand and how fast? What feedback structure mainly determines the periodicity and what feedback loops drive the rate of convergence or divergence in the cycles.

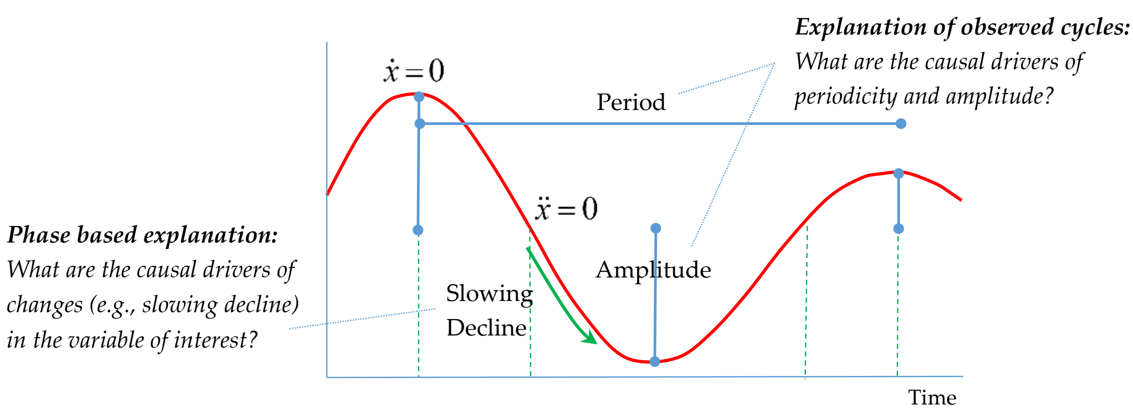


Figure 1: The focus shifts from changes in the variable of interest in the phase-based explanation to the properties of observed cycles and the underlying causal structure

Phase-base explanation: In the phase-base method of explanation, a cycle observed in the behavior of the variable of interest is implicitly or explicitly divided into multiple phases. The phases are often sliced according to slope (first time derivative) and curvature (second time derivative) of the variable of interest (Mojtahedzadeh, 1997). Similarly, Ford (1999) defines the concept of "atomic patterns" with second time derivatives of the variable of interest and suggests, “Combinations of the three atomic behavior patterns can describe most behavior simulated by system dynamics models.” Saleh (2002) also defines behavior pattern index as “the ratio of the curvature to the slope” of the variable of interest to tease out the “convergent” from “divergent” patterns. Other aspects of dynamic behavior, which are characterized by higher order derivatives, may have less applicability in real world situations and may not be necessary in tracing the dominant feedback structure that drives it (Mojtahedzadeh, 1997).

In the absence of formal methods for detecting the feedback structure that dominates in each phase, modelers rely on simple heuristics, repeated simulations, experience and intuition to trace a causal chain that contributes to the rates of expansions and contractions in the variable of interest in each phase. Experienced modelers with one eye on the equation and another on the dynamics of the variables leading to the variable of interest identify the most influential variable and follow back until they feel they have understanding of the causal chain that represent the dominant structure.

Mass and Senge (1975) were the first to formally describe this method in a simple workforce-inventory model to provide “intuitive explanations of the causes of convergent, divergent and un-damped oscillations.” Graham (1977) calls this approach “disturbances from equilibrium” as the focus is on the causal factors that most contribute to the departure of the variable of interest from equilibrium and eventually bring it back to the equilibrium.

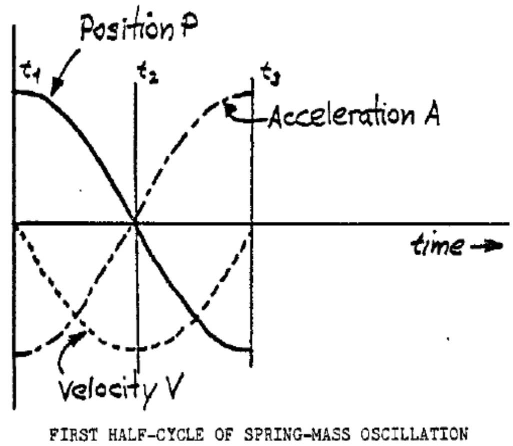


Figure 2: Explaining a Spring-Mass Cycle by its using Mass-Senge approach (from Graham, 1977, Reproduced by permission of MIT System Dynamics Group

Graham applies the method to simple pendulum model to explain the cycles in spring-mass oscillation. The two phases of Position, Velocity and Acceleration are depicted in Figure 2 borrowed from Graham’s thesis. He describes why the Position declines as Acceleration picks up: “…the first quarter-cycle of the oscillation, the Position greater than zero causes a negative Acceleration, causing Velocity to decline. As the Position approaches zero, the Acceleration goes to zero, and the Velocity temporality ceases to changing….. .” (Page 62).

In his seminal work, market growth, Forrester (1968) utilizes a similar approach to describe how a half-cycle in backlog takes place and what part of the structure drives it. Figure 3, borrowed from Forrester's paper (page 13), the behavior of backlog and it two phases of an observed cycle identified by equilibrium points. Forester describes, "The rate of order booking is initially too high because of the low backlog and the low delivery delay. But the order rate in excess of delivery rate causes backlog to rise [Phase 1] and causes the delivery delay recognized by the market to rise. Sales effectiveness and orders booked fall. The rate of order booking declines below the delivery rate, thereby causing a decline in the order backlog [Phase 2]."

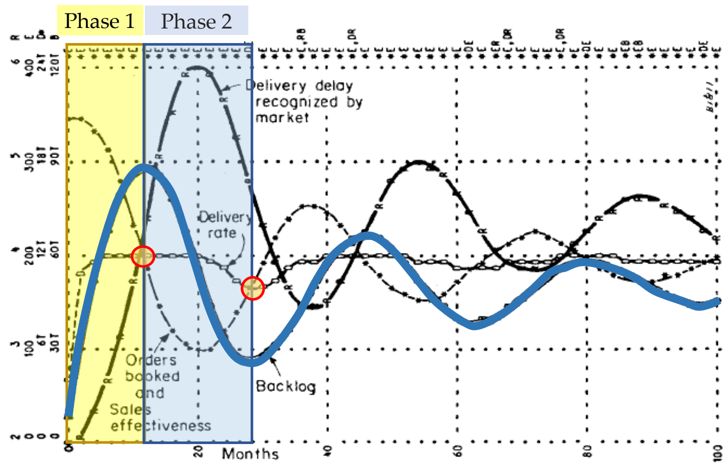


Figure 3: Cycles in Forrester Market Growth Model: Balancing growth and reinforcing decline phase of a cycle in backlog is highlighted (from Forrester, 1968, Reproduced by permission of MIT System Dynamics Group)

Phase-base explanation is intuitive; it begins with the variable of interest and identifies the partial structure the causes the observed behavior of the variable of interest to change. However, it may not explicitly detect the dominant structure. Graham argues: "The explanation itself does not clearly identify underlying structures necessary for oscillation in general (even though… begin to)". Furthermore, phase-based expiation is intrinsically local and partial as it focuses merely on the variable of interest observed from simulation results. The explanation remains silent about the properties of the cycles and does not tell "What happens if we change a parameter? Why is the period constant? Why is the period what it is? … " (Graham, 1977).

Explanation of observed cycles: Four consecutive phases in the behavior of the variable of interest identified according to slope and curvature, make up a complete cycle. In the explanation of observed cycles, the focus shifts from how a cycle takes place and what contributes to the attributes of the observed cycle as a whole (Mojtahedzadeh, 2007). The commonly used properties of cycles include periodicity and amplitude, but several other properties have been developed to understand the nature of oscillatory systems from different perspectives (Forrester, 1983, Sterman 2000). The explanation of observed cycles is no longer around changes and rates of expansions and contractions in the variable of interest; rather on the property of cycles as a whole and how those properties change over time.

Nathan Forrester (1983) introduced a formal analysis of cycles in the context of an oscillatory economic model. While utilizing different attributes of cycles, including damping measure, Forrester (1983) defines various criterions for stabilization, such as the one depicted in Figure 4 that quantifies the effect of stabilization policy with "the speed of convergence of an oscillation to equilibrium" (page 28). Clearly, the focus in this analysis is solely on the attributes (e.g., rate of decay) of the cycle and feedback structure that drive those attributes.

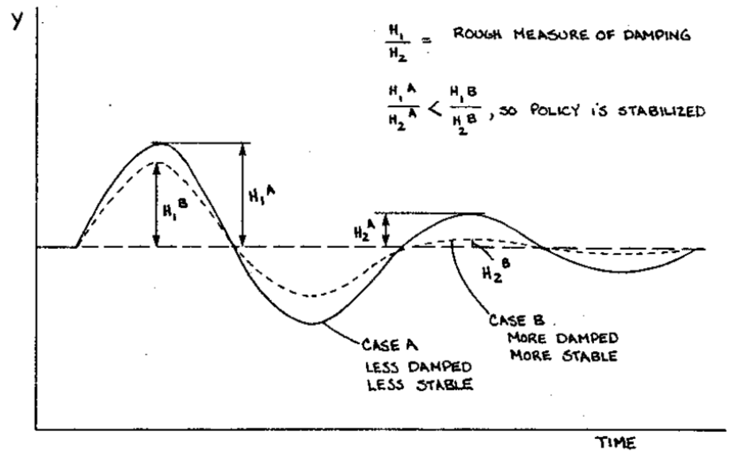


Figure 4: Damping attribute of cycles for quantifying Policy impacts (from Forrester, 1982, Reproduced by permission of MIT System Dynamics Group

In the market Growth model, the phase between two equilibrium points, highlighted in Figure 3, forms a half-cycle that according to Forrester is driven by loop 2, "a major loop that connects delivery delay of the market, generates sales effectiveness, and influences the rate of orders booked…. Here the loop tends to adjust the rate of order booking to equal the delivery rate … Because of the three delays around the loop … the adjustments may occur too late and cause a fluctuating condition in the system…Fluctuations of decreasing amplitude continue over the period of 100 months shown in the figure". One might argue that the explanation in here is shifted from the details of what causes the rise and fall of backlog to an overall description for drivers of periodicity and amplitude in cycles observed in the variable of interest. Forester does not explicitly speaks of the feedback loop(s) that causes the decreasing amplitude in here, however, he points out that the balancing major that connects delivery delays to sales effectiveness, and orders booked causes the observed fluctuations.

Identifying causal drivers of the properties of cycles—what feedback structure drives the periodicity and what determines amplitude -- require extensive experience in working with dynamic systems. To support the intuition of modelers, Graham (1977) developed heuristics to help in the detection of the underlying feedback structure that generate oscillatory behavior.

Nathan Forrester (1983) introduced eigenvalue elasticities to detect dominant structure responsible for creating modes of behavior in the system. He observed number properties that in properties in eigenvalue elasticities that made it suitable for connecting behavior modes to the feedback structure (Forrester, 1983; Richardson 1986; Mojtahedzadeh 1997, Kampmann et al 2007). The system dynamics literature on model analysis extensively describes challenges facing eigenvalue elasticity approach, including two fundamental problems whose solutions are still in work:

1. *Dominant loop depends on the lay out of the model structure*: Kampmann (1996) discovered that dependency in feedback loops can distort the analysis and "it only makes sense to speak of individual contributions of a limited set of independent loops." However, there may not be a unique set of independent loops in a system dynamics models and it would depend on the context and lay out of the structure, not necessarily the underlying mathematics (Mojtahedzadeh 2009), which can lead to "phantom loops" (Kampmann et al, 2008).
2. *Connecting eigenvalue analysis to the simulation results:* System eigenvalues are "abstract concepts and their connection to real world situations is not easily established. Furthermore, relating eigenvalues and their sensitivities to the time-space continuum is very difficult, if not impossible." (Mojtahedzadeh, 1997, page 150). Kampmann et al (2007) views the difficulty in interpretation of the eigenvalues as "the most serious theoretical issues" and suggests: "There is a need for tools and methods that can translate them into visible, visceral, and salient measures."

Pathway Participation Method

Pathway participation approach (Mojtahedzadeh, 1997, 2004, 2007 and 2009) was developed, based on the formal definitions of loop polarity and shifts in dominant polarity by Richardson (1996), to detect dominant structure that generates the observed behavior of the system. Figure 5 depicts a schematic for the process of detecting dominant structure using pathway participation method. It starts with selecting the variable of interest. In pathway participation method, the structure is characterized by the derivative of net flow with respect to the variable of interest. The participation metrics for all the pathways leading to the variable of interest is calculated in every time step. The sum of those participation metrics, total pathway participation metrics, is effectively the ratio of second and first time derivatives that characterizes by the observed over time behavior of the variable of interest. The dominant pathway is defined according to pathway whose participation metric is larger and has the same sign and total pathway participation metrics. The search algorithm for the detection of dominant structure is based on the dominant pathways that are causal chains that start with a system stock variable and lead to the variable of interest. Hayward et al (2014) offers an alternative search algorithm for identifying dominant structure using pathway participation metrics.

For the oscillatory systems, the pathway participation method support both phase-base and explanation of observed cycles. It identifies the dominant structure for four phase of oscillation to detect what structure causes changes in the variable of interest. It also identifies the dominant structure for the observed cycles to explain what feedback loops drive the periodicity and convergence in oscillation. For the explanation of observed cycles, the pathway participation method focuses on the beginning and end of half-cycle characterized where the first time derivative of the variable of interest is zero and the middle of half-cycle. Using these points, two measures of frequency and convergence (stability) factor are calculated and dominant pathway are identified (for more details see Mojtahedzadeh, 2007 and 2009)

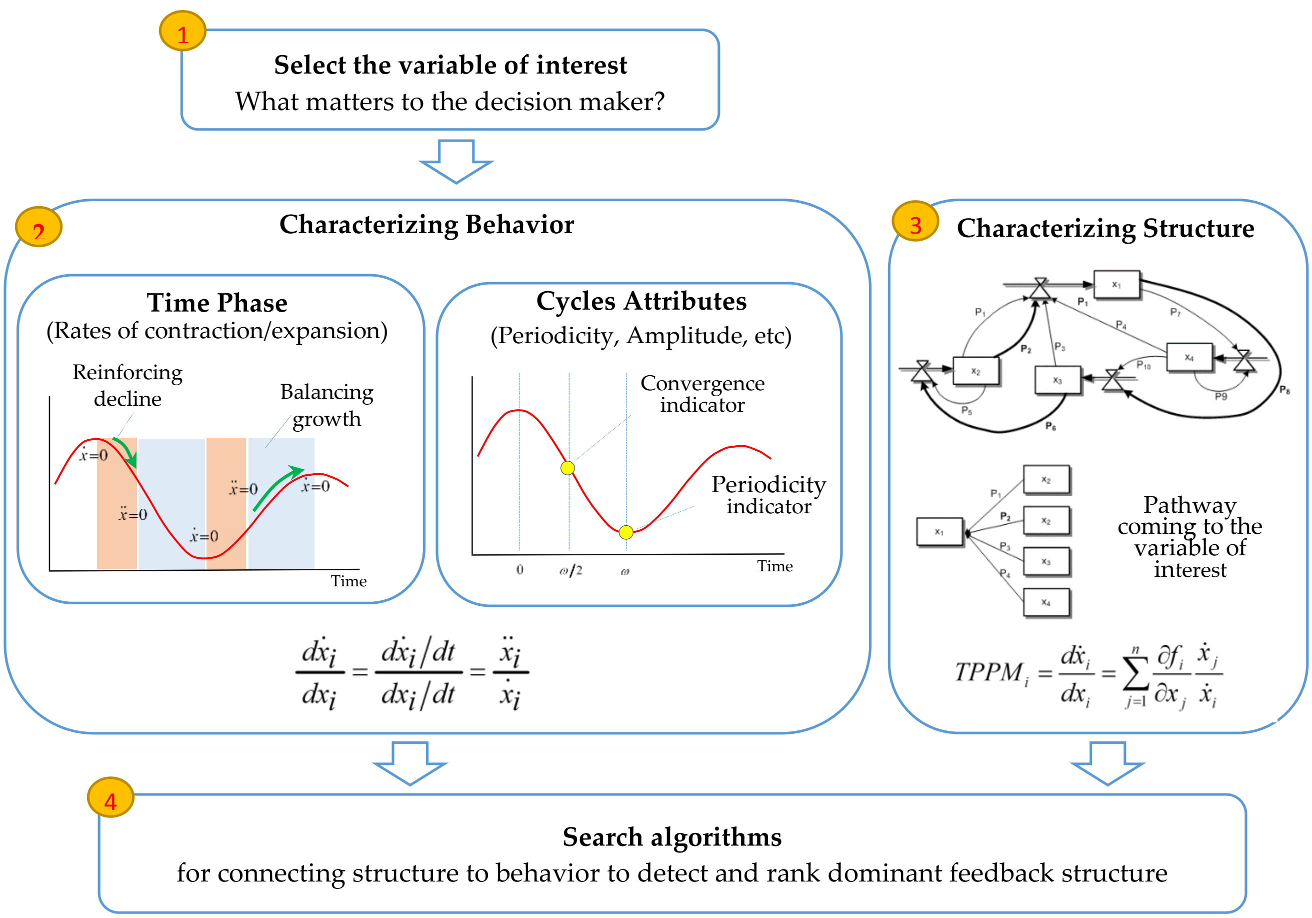


Figure 5: Schematic display of loop dominance detection in pathway participation method

- It has been shown that pathway participation metrics and eigenvalue elasticities converge in steady states for oscillatory and non-oscillatory systems. Perhaps the similarities of the metrics explain why the two approaches can produce similar results. (Mojtahedzadeh, 2008; Güneralp, 2006; Oliva et al, 2004)
- Unlike eigenvalue elasticity approach, the pathway participation method is closely related to the observed behavior. Therefore, it is easier to interpret the results. The reason is that the first and second derivative that characterizes the behavior is effectively equal to the derivative of the net flow with respect to the variable of interest that drives the dominant structure.
- Unlike eigenvalue elasticity approach, the pathway participation method identifies dominant structure based on pathways defined by the mathematical equations. Consequently, it remains independent of the context (the chosen independent loop set in eigenvalue elasticity approach) and the layout of the model structure. Therefore, it circumvents the problem of phantom loops and hidden loop is system dynamics models.

Identifying the dominant structure based on pathways presents two challenges particularly when it comes to explaining complex patterns observed in the system behavior. One challenge is the characterization of pattern of interest from simulation results. For explanation based on departure from equilibrium, behavior charactrized by first and second time derivative may be sufficient. However, for cycle-based explanation, one should develop the appropriate metrics from observed behavior for characterizing and attribute of interest in the cycles (e.g., frequency, amplitude). For explanation of more complex patterns of such as the one shown in Figure 6 trends in cycles may be a metric of interest. Trends in cycles are not attributes of oscillation; however, their interactions with cycles can make explanation of observe behavior more challenging.

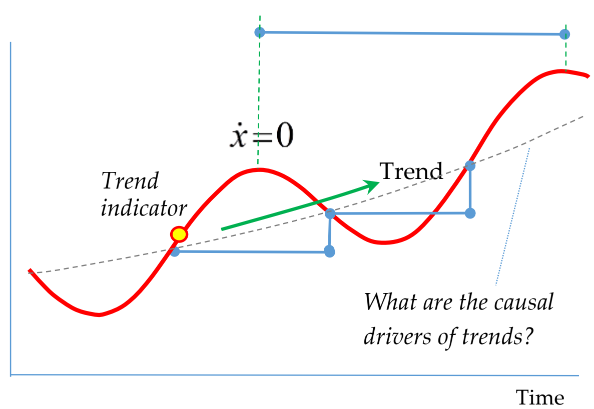


Figure 6: Cycles with a growth trend. Trend indicator is where participation metrics equals the growth rate of the observed trend

The second challenge is to ensure that a collection of dominant pathways, level-to-level coupling, makes up the correct dominant feedback. The pathway participation approach has relied merely on case studies of relatively simple dynamic models to verify whether level-to-level coupling heuristic leads to sensible dominant structure. For simple oscillatory systems, it has been shown, through several case studies, that connecting dominant pathways detected based on frequency and stability factors may form intuitively sensible dominant feedback structure. Would local detection of dominant structure lead to a global insight in larger scale system dynamics?

Explaining Cycles in Forrester's Market Growth Model

Forrester's (1968) presents a dynamic market growth model to show that a firm's performance in the market (e.g., delivery delays) and its operating policies (hiring salesmen and production capacity) can interact and create growth and stagnation that "cannot be intuitively appreciated". Forrester describes the behavior of the model under various conditions in terms of the feedback structure. This section presents the application of pathway participation metrics in analyzing the cyclical behavior in the market growth model presented in Figure 8, 13 and 14 in Forrester's paper.

Three graphical functions are used in the model are reformulated in terms of some polynomials that tightly correlated with the original graphical function. This significantly reduces small discontinuities in the graphical functions that can potentially influence the calculations. The variable of interest in this analysis is backlog that oscillates in most simulation runs. Figure 7 shows all the pathways coming into backlog one of which will be detected as dominance in creating the changes in variable of interest and the properties of the cycles it exhibits. This dominant pathway along with other dominant pathways identified in the behavior of stocks that influence the variable of interest make up the dominant structure.

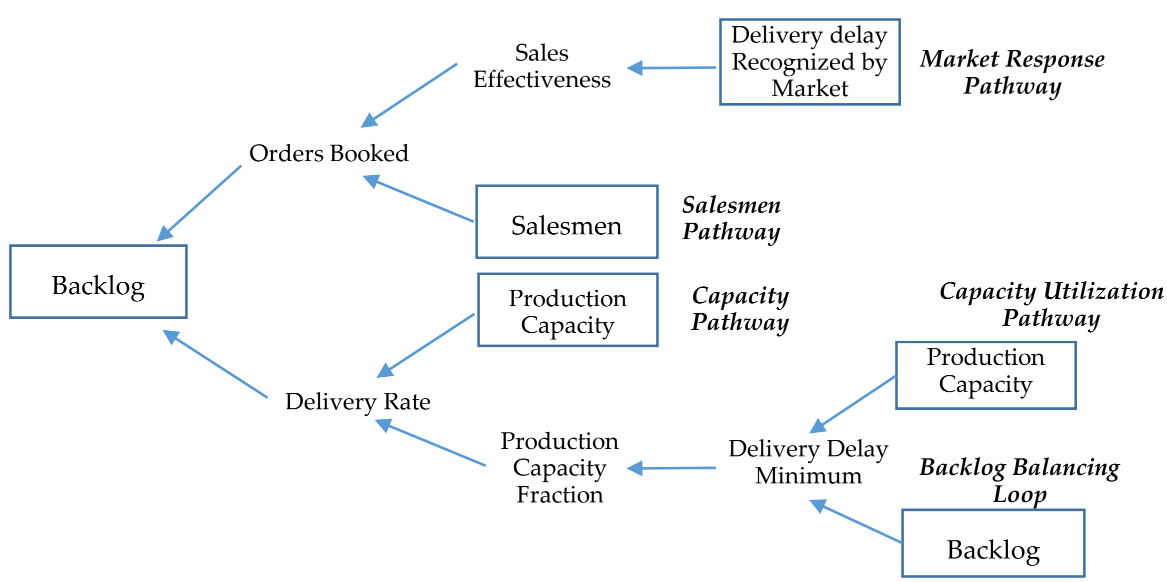


Figure 7: Pathways coming to backlog defined as the sequence of links that begins with a stock variable and ends with the variable of interest

Fluctuation in Backlog

Fluctuations in backlog, shown in Figure 3, and discussed in the previous section is the result of a balancing feedback loop around order backlog, delivery delay recognized by company and delivery delay recognized by market, shown in Figure 8. As noted in the previous section, to explain the cycles in backlog, Forrester focuses on two points in time where orders booked equal delivery rate, which are essentially equilibrium points in backlog.

Pathway Participation Analysis of damped Oscillation in Backlog

Figure 9 depicts the dominant pathway detected by PPM in various phases of the behavior of backlog that are identified by first and second time derivatives. As discussed in the previous section, Forrester uses the time slices between the two equilibrium points to explain the changes in backlog. The pathway participation approach, however, further breaks down the phase with inflection points where the second time derivative is zero. This will help to better focus on the causal factors that slow down and speed up the changes in backlog. There is another point in time that ppm focuses on, the middle of the two equilibrium points, as it tells something about the stability of cycles in the variable of interest. Despite the difference in details, both phase based and explanation of cycles in backlog using ppm is consistent with Forrester's intuition.

According to pathway participation metrics, among five pathways coming to the variable of interest, shown in Figure 7, the market pathway is dominant as backlog approaches its first equilibrium point. The dominant market pathway in the rising backlog causes reductions in sales effectiveness, and therefore slows down the growth in the variable of interest and later causes it to decline. The backlog's balancing loop becomes dominant for a short period to prevent further decline in backlog and market pathway takes over to drive backlog slowly to its new equilibrium followed by a reinforcing growth.

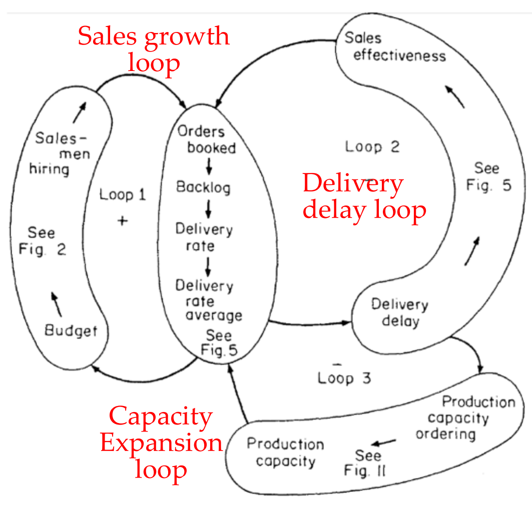
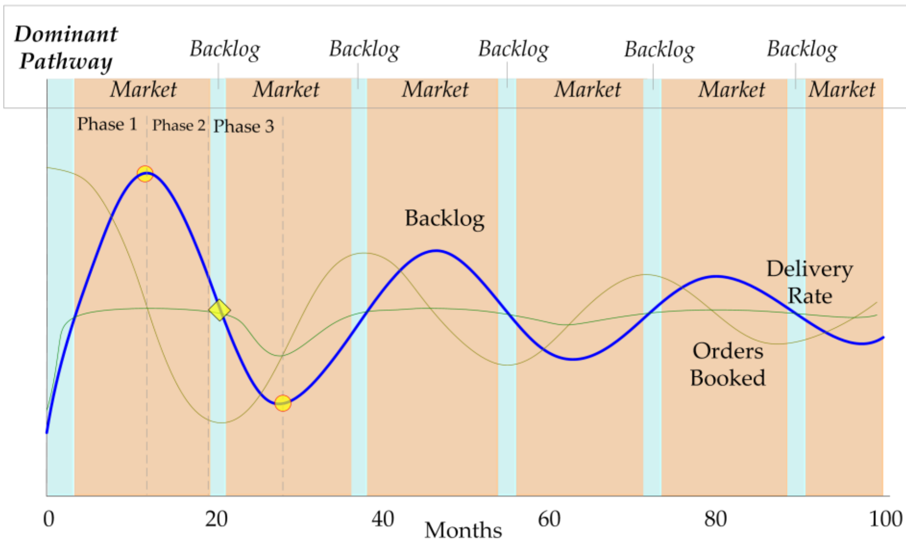


Figure 8: Loop structure for sales growth, delivery delay, and capacity expansion (from Forrester, 1968, Reproduced by permission of MIT System Dynamics Group)

Pathway participation approaches identifies the third-order delivery delay loop, loop 2 in Figure 8, is responsible for the periodicity of the observed 17 months half-cycles while minor first order loops around the stock variables drive the stability of those half-cycles. The dominant loop are detected based on the information in frequency and stability for backlog, reported in Table 1, and delivery delay recognized by market and company, not reported in here.



For explanation of cycles, dominant pathways are identified based on participation metrics around circles and diamond, which indicate the periodicity and stability of cycles respectively.

Half-cycles	duration	month	factors	Total	Market pathway	Backlog loop	Dominant
1	16.9	11.7	Freq.	0.19	***0.19***	0	Market path
		20.1	Stab.	-0.031	0	**-0.032**	Backlog loop
2	17.7	28.6	Freq.	0.18	***0.18***	0	Market path
		37.5	Stab.	-0.011	0.014	**-0.025**	Backlog loop
3	17.6	46.3	Freq.	0.18	***0.18***	0	Market path
		55.1	Stab.	-0.023	0	**-0.023**	Backlog loop
4	17.1	63.9	Freq.	0.18	***0.18***	0	Market path
		72.5	Stab.	-0.021	0	**-0.023**	Backlog loop
5	17.4	81	Freq.	0.18	***0.18***	0	Market path
		90	Stab.	-0.023	0	**-0.023**	Backlog loop

Table 1: Pathway frequency and stability factors for the half-cycles in backlog (Dominant pathways are highlighted)

Explaining Unstable Growth

Forester (1968) examines the impact of capital expansion in response to delivery delay that results in unstable growth in a number of variables in the model including backlog. Figure 10 depicts the consequential behavior when capital expansion loop along with sales growth loop are added to the market response loop discussed in the previous section. To explain the emergent behavior, Forrester shifts the focus on equilibrium points that was used to explain cycles caused by delivery delay loop to four points in time where orders booked are meet production capacity "because in the long run, average orders cannot exceed capacity". Forrester observes "a repeating fluctuation of capacity and order rate crossing one another" while production capacity grows over time.

Based on the new heuristic, one sees four points in time where production capacity and orders booked cross. It happens in months 24, 40 70 and 84 and for distinct phase that help to explaining cyclical behavior in capacity order rate crossings.

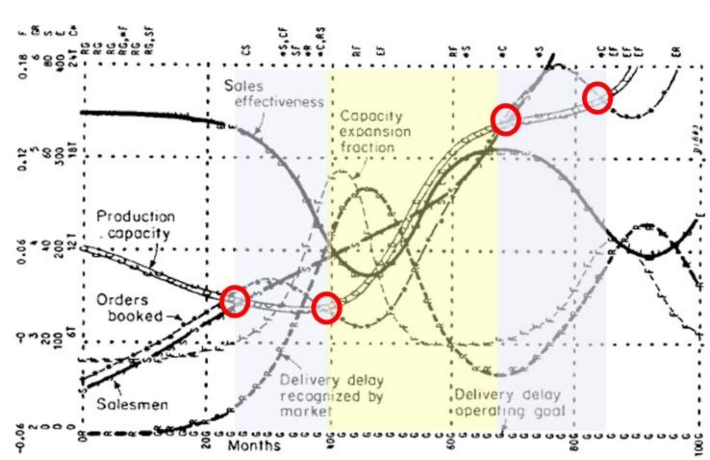


Figure 10: Growth with cycles in Forrester market growth Model. Capacity and order rate crossings are marked in circles (from Forrester, 1968, reproduced by permission of MIT System Dynamics

Before the first crossing in month 24: As Forrester describes, during this time "production capacity … is well above the initial rate of sales". Salesmen, orders booked and backlog grows rapidly and thus production capacity is diverted. "The rate of order booking rises above the production capacity at about the 24th week."

Before the second crossing at month 40: During this period "order backlog is rising rapidly, capacity is failing slowly, and the delivery delay is climbing steeply."

Before the third crossing at month 70: The increasing delivery delay leads to additional capacity ordering. Higher capacity, in one hand, boost sales effectiveness and thus orders booked and on the other hand "it signals a reduction in the rate of capacity expansion; and production capacity levels off around the 70th week."

Before the fourth crossing at month 84: A rising orders booked along sluggish increase capacity causes an increase in delivery delay and the story repeats.

It seems that Forrester indicates that fluctuations in capacity and order rate crossings are mainly driven by "High delivery delay simultaneously causes the expansion of capacity and the suppression of orders." Delivery delay loop, loop 2 and capacity expansion loop, loop 3, in Figure 8 adapted from Forester's original paper depicts the feedback processes for the dual impact of delivery delay which Forrester identifies as the source fluctuations in the system.

Pathway Participation Analysis of Unstable Growth

Figure 11 depicts the behavior of the backlog and the dominant pathways at any point in time. The squared, triangle and diamond markers indicate aspects of the observed cyclical behavior and populated based on pathway frequency, stability and growth factors shown in Table 2. The circle markers indicate the point where production capacity and backlog cross, the heuristic that Forrester has used to explain the fluctuations of the dominant feedback structure that drives those fluctuations. One can easily see that pathway participation approach picks up points in time in the close proximity of capacity-backlog crossing heuristics, although it focuses on a few additional points to detect the dominant structure.

The pathway participation story of backlog dynamics in terms departure from equilibrium can be told with the phase of dominant pathways as shown in Figure 12 (Mojtahedzadeh, 1997). In the booming phase, when the total participation metrics remain positive, backlog is driven by is mainly influenced by the salesmen pathway. A growing salesman increases orders booked, backlog and assuming sufficient production capacity, delivery rate that in turn, provides increased budget for hiring and thus more salesmen. In the rise and fall phase, the market pathway dominates, in month 29, and backlog growth slows down followed by a decline due to poor sales effectiveness driven by delivery delay. Capacity pathway dominates about month 40, and production capacity expands; delivery rate raises which causes further decline in backlog. The negative backlog balancing dominates in 45 to regulate the falling backlog. Around month 47, the market path dominant and backlog enters the fall and rise phase because of booming sales effectiveness and orders booked due to lower delivery delay. The story repeats once salesmen pathway overtakes the orders book in month 58 and backlogs grows rapidly.

The explanation of observed cycles according to pathway participation metrics is based on specifics of participation metrics for backlog shown by makers in Figure 11. There are two long half-cycles, averaging about 33 months, and two shorter half-cycles of 13 months in backlog. Table 2 suggests that salesmen pathway is dominant in the first half-cycle. This pathway and the dominant pathway in the salesmen and delivery rate average stocks around in the same time form the sales reinforcing loop, shown as loop 1 in Figure 8, that gives rise to the first half-cycle. However, story changes as the backlog approaches the second half-cycle. As shown in the Table 2, in the beginning of the rest of the half-cycles the market response pathway dominates, which, in turn, is driven by delivery delay recognized by company pathway. However, as Figure 12 depicts, the dominant pathways for the periodicity of the half-cycles in delivery delay recognized by company follows two different routes. One is the link that connects back to backlog and delivery delay loop, loop 2 in Figure 8, and the other is the pathway the connects to delivery delay average, production capacity and returns to delivery delay recognized by company and forms the capacity expansion loop, loop 3 in Figure 8. As shown in Figure 13, the former occurs when delivery delay recognized by company is at its booms, and the latter occurs when it is at its lowest value. These are the two feedback loops that Forrester (1968) uses to explain the fluctuations in capacity and order rate crossings as "High delivery delay simultaneously causes the expansion of capacity and the suppression of orders."

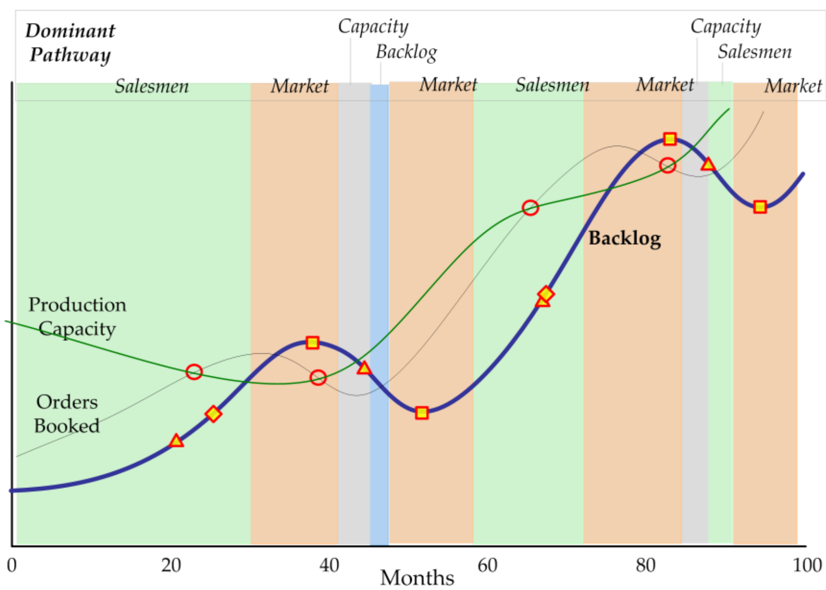


Figure 12: Growth with cycles in Forrester market growth Model. Capacity and order rate crossings are marked in circles. The squared, triangle and diamond markers indicate frequency, stability and growth factors shown in Table 2

Forrester does not discuss the stability or the trends in capacity-order rate crossings fluctuations in this particular simulation run. The pathway participation approach suggests that the sales growth loop, loop 1 in Figure 8, dominates and creates the growth trends in the backlog's observed cyclical behavior[1]. Table 2 shows that the

[1] To detect the dominant feedback loop in the observed trend, PPM calculates the average growth in the variable of interest during mid-points in two consecutive half-cycle, finds the closet total participation metrics and identify the dominant pathway, accordingly.

dominant growth factors for half-cycle is the salesmen pathway, this and the dominant pathway for growth factors in salesmen and delivery rate average, not reported in here, forms the sales growth loop, loop 1 in Figure 8. The pathway participation analysis also suggests that half-cycles in backlog are unstable and is mainly caused production capacity pathway for the cycles with shorter periodicity and salesmen pathway for the longer cycles.

half-cycles	Duration	Month	Factors	Total	Market pathway	Salesmen pathway	Capacity pathway	Capacity Utilization	Backlog loop	Dominant
1	35.3	2	Freq.	0.09	*0*	**0.09**	0	0	0	Salesmen path
		20	Stab.	0.08	-0.033	0.282	0.044	0	-0.216	Salesmen path
		28	Growth	0.02	-0.1	0.12	0.03	0	-0.03	Salesmen path
2	14	37.3	Freq.	0.22	***0.22***	-0.07	0.05	0	0	Market path
		44	Stab.	0.06	-0.001	-0.062	0.166	0	-0.041	Capacity path
3	31.2	51.3	Freq.	0.1	***0.11***	0.033	-0.041	0	0	Market path
		67	Stab.	0.04	-0.018	0.19	-0.030	0	-0.1	Salesmen path
		70	Growth	0.02	-0.068	0.168	-0.024	0	-0.055	Salesmen path
4	12	82.5	Freq.	0.26	***0.28***	-0.19	0.16	0	0	Market path
		89	Stab.	0.02	-0.013	-0.177	0.263	0	-0.047	Capacity path

Table 2: Pathway Frequency, Stability and growth factors for the half-cycles in backlog (Dominant pathways are highlighted)

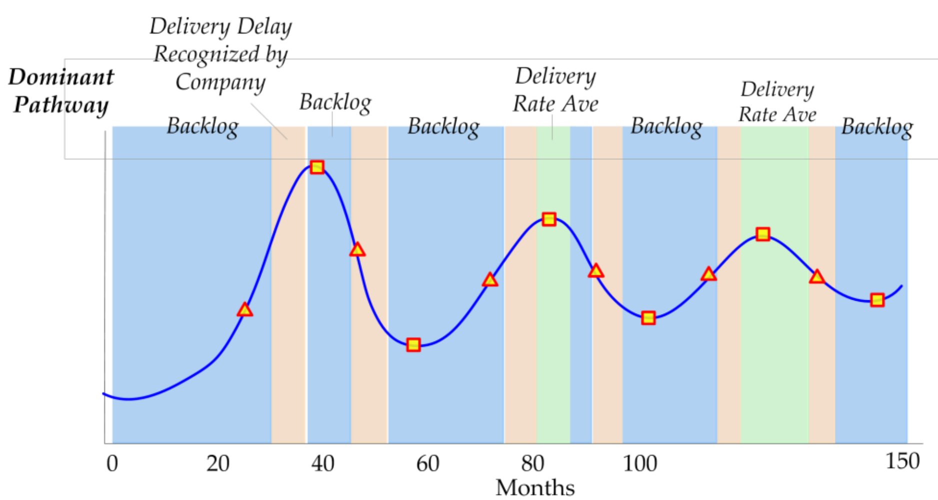


Figure 13: Cycles in delivery delay recognized by Company and its dominant pathways. The squared, triangle markers indicate frequency and stability of observed half-cycles. The delivery delay recognized by company is at it min, frequency of the cycles are driven by the pathway that connects it to backlog. This dual impact of delivery delay indicates cycles are driven by two loops; delivery delay loop and capacity expansion loop.

Explaining Decay with Cycles

Production capacity collapses when capacity expansion decisions are based on past performances rather than a fixed and low goal. Figure 14 depicts how stagnation turns into decay because of this decision rule and highlights capacity- orders booked crossing that occurs while the system go through the decay. Forrester explains: "As capacity goes down, the rate of order booking declines to correspond, because in the long run, average orders cannot exceed capacity… Sales effectiveness declines, the revenue to sales declines, and the revenue become insufficient to support the existing number of salesmen. After about the 70th week the number of salesmen begins to decrease …"

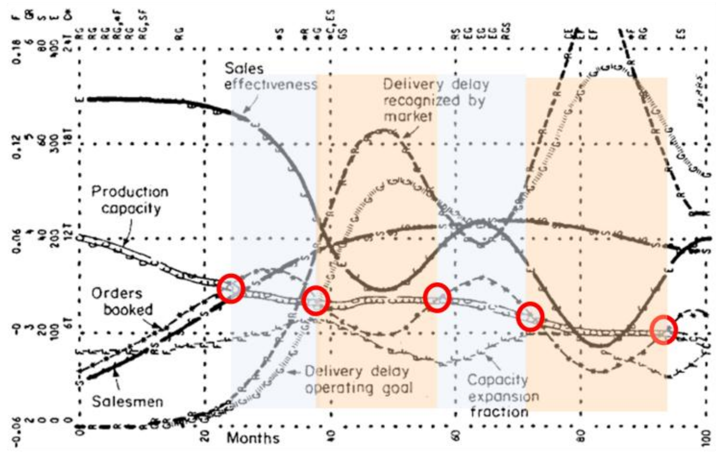


Figure 14: Decay with cycles in Forrester market growth Model. Capacity and order rate crossings are marked in circles (from Forrester, 1968, reproduced by permission of MIT System Dynamics

Pathway Participation Analysis of Cyclical Decay

Figure 15 depicts the behavior of the backlog and the dominant pathways at any point in time. The dominant pathway around triangle and diamond markers indicate aspects of the observed cyclical behavior and populated based on pathway frequency stability and growth factors shown in Table 3. The circle markers indicate the point where production capacity and backlog cross, the heuristic that Forrester has used to explain the fluctuations of the dominant feedback structure that drives those fluctuations. One can easily see that pathway participation approach picks up points in time in the close proximity of capacity-backlog crossing

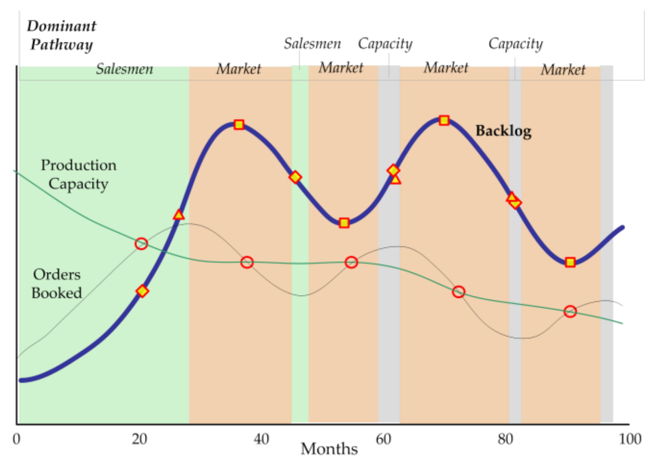


Figure 15: Cycles with decay trend in Forrester market growth Model.

heuristics, although it focuses on a few additional points to detect the dominant structure.

There is one long half-cycle, 37 months and four shorter half-cycles varying between 14 to 19 months. According to the pathway participation metrics, just like in Figure 12, the first half-cycle is dominated by sales growth loop; however, this dominance shifts to delivery delay loop, loop 2 in Figure 8, as the driver of the periodicity in cycles. Table 3 indicates that the market pathway dominates the periodicity of half-cycles. This pathway along with dominant pathways for delivery delay recognized by market and company, not reported in here, form the third order delivery delay balancing loop, loop 2 in Figure 8.

The first half-cycle in backlog exhibits a growth trend driven by sales growth loop--loop 1 in Figure 8. The dominant pathway for the growth factor of the first half-cycle in backlog, salesmen pathway according to Table 3, along the dominant pathways for the factor in salesmen and delivery delay average makes up the sales growth loop. The stagnation and decay trend in rest of the backlog's half-cycles is driven by production capacity while the downward trend in production capacity is mainly driven by the minor loops around the third order delay in production capacity and its expansion.

half-cycles	Duration	Month	Factors	Total	Market pathway	Salesmen pathway	Capacity pathway	Capacity Utilization	Backlog loop	Dominant
1	37.2	2	Freq.	0.08	*0*	**0.08**	0	0	0	Market path
		20	Stab.	0.07	-0.05	0.27	0.05	0	-0.2	Salesmen path
		29	Growth	0.03	-0.11	0.13	0.04		-0.03	Salesmen path
2	16.2	39.2	Freq.	0.19	***0.25***	-0.06	0	0	0	Market path
		47	Stab.	-0.02	***0.03***	***-0.03***	0.01	0	-0.03	Backlog loop
			Decay							
3	16.9	55.4	Freq.	0.19	***0.16***	0.02	0.01	0	0	Market path
		63.9	Stab.	-0.03	-0.04		0.05	0	-0.04	Salesmen path
			Decay					0		
4	18.9	72.3	Freq.	0.16	***0.2***	0.01	-0.05	0	0	Market path
		81.8	Stab.	0	0.01	**0.01**	-0.02	0	0	Capacity path
5	14.5	91.3	Freq.	0.21	0.21	-0.04	0.04	0	0	Market path
		98.5	Stab.	0.02	-0.02	-0.04	0.08	0	0	Capacity path

Table 3: Pathway Frequency, Stability and growth factors for the half-cycles in backlog
(Dominant pathways are highlighted)

Conclusion
Simulation reveals what the consequence of a feedback system is; however, it remains silent and mysterious about why. Identifying dominant structure to uncover why a system does what it does has been one of the central challenges in system dynamics modeling practices. Oscillatory systems are even a harder nut to crack. Two different approaches are used to explain cyclical behavior of systems. One is phase-based explanation that focuses on partial system structure and investigates changes in the system variables as it goes through the oscillation. The other is the explanation of cycles with global view and analyzes various attributes of cycles including, but not limited to, frequency and amplitude. One challenge with the eigenvalue elasticity method developed to support the latter explanation, has been connecting global measures of cyclical behavior, complex eigenvalues, to the simulation outputs. Pathway participation approach begins with phase-base explanation and local stories of partial structure and strives to arrive at explanation of global attributes of observed behavior. This paper shows pathway participation approach can successfully support both explanations for cyclical behavior in Forrester's classic market growth model. More case studies are needed to ensure that starting with local stories and partial structure and identifying dominant structure with level-to-level connections can lead to system level stories of the whole structure for system level insight.

This paper argues that a few critical points in the variable of interests are likely the key to understanding the cyclical behavior the system exhibits. In explaining market growth model Forrester uses two heuristics, one is equilibrium points in backlog, Figure 5, and the other is orders booked and capacity crossings, Figure 12 and Figure 14. According to pathway participation, understanding the equilibrium points, the beginning and end of half-cycle helps in characterizing periodicity of the observed cycles while analysis of the middle points of half-cycles reveal the stability characteristics of the half cycles. For the cycles that are riding on a trend, like in market growth models, a point in time close to the inflection point of half-cycles is perhaps a good heurist to detect the dominant the structure for the trend. The higher the growth (or decay) of the trend the further this point should be from the inflection point. These are only heuristics to support intuition, not to replace it.

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