Constraint Theory
A Logic-Based Approach to System Improvement
by H. William Dettmer

ABSTRACT

The Theory of Constraints (TOC), developed by Dr. Eliyahu M. Goldratt, offers a methodology for achieving system optimization, rather than process maximization. By synchronizing an organization as an integrated whole, instead of a collection of related parts, higher levels of system performance can be achieved more quickly. TOC provides a series of guiding principles and concepts, supported by a set of logistical tools to manage work flow through the system and a set of logical tools (trees) to identify system constraints and design and implement effective ways to break them. Hundreds of companies, large and small, have realized major successes with TOC and its tools. Noteworthy among these companies are Bethlehem Steel, Ford Electronics, Harris Semiconductor, and General Motors, whose cases are summarized in this paper. Hundreds of other smaller companies in every conceivable business from software engineering to health care have also applied TOC principles and tools. After introducing constraint theory and explaining its relationship to system management and organizational change, this paper concentrates on the five logical tools Goldratt developed to identify, exploit, and even break constraints to better organizational performance. Examples of the logic trees in various familiar situations are provided.

It is a simple task to make things complex,
but a complex task to make them simple.

The complexity of our environment and the systems within it grows almost daily. The business world, government, and social systems were all far less complicated 70 years ago than they are today. As communication makes the world smaller and its elements more interactive, these environments are likely to become even more complex in the future. The dynamic, ever-changing nature of the environment virtually guarantees challenges of the "adapt-or-die" type to all our systems: business, education, social, and political.

SYSTEM COMPLEXITY

Adaption implies change, and the more complex the system, the more difficult change is to cope with. Besides complexity, however, several other factors conspire against the chances of first-time successful change. One is the aforementioned dynamic, ever-changing nature of the environment. It's tough to hit a moving target. Another is the uncertainty posed by variation and the dependent nature of system components. A third is the natural tendency to compartmentalize component activities within systems organizationally rather than to integrate them functionally. In other words, we tend to manage by the organization structure than by the natural functional flow of work through the system. This usually leads to a fourth factor: local optimization at the expense of the well-being of the whole system.

THE CHALLENGE

Organizations live or die as complete systems, not as a collection of discrete processes. In the dynamic, complex environment of both today and tomorrow, we face a pressing challenge to make our systems function effectively as well-integrated machines, rather than as a collection of compartmented, suboptimized processes.

The North American Free Trade Agreement

Take, for example, the North American Free Trade Agreement (NAFTA). This was an agreement negotiated by politicians, with some input from the business community (and a lot more from politicians and lobbyists), but very little from other segments of American society. As a consequence, the agreement was flawed. It experienced fits and starts during implementation, has yet to live up to the original expectations for it, and has created some frustrating new problems that didn't previously exist.[1] These problems might have been avoided with effective system engineering, but they were not. What's worse, the Clinton administration is now bent on extending NAFTA throughout the western hemisphere, with no indication that they've learned the lessons of the original agreement. If the past is any indication of the future, we can expect the economic well being of America to be suboptimized to narrow, short term political interests.

Digital Equipment Corporation

On a considerably smaller scale is Digital Equipment Corporation (DEC). In 1992, DEC found itself in decline under co-founder Kenneth Olson.[2] The DEC board of directors brought in Robert B. Palmer as CEO to run DEC. During the next two years, Palmer restructured the company twice, but DEC still lost $4 billion between 1990-94. So Mr. Palmer tried again. The third restructuring created nine new business units, three of which reported directly to Palmer. Some top executives were fired, and the work force was reduced from 92,000 to 65,000. At the time, Mr. Palmer was quoted as saying, "The marketplace is too Darwinian to allow [excessive talks and memos, blurry responsibilities, and slow decisions]. We will be more agile and we will be more decisive."[3]

Three years later, DEC had not achieved the big turn-around. Revenue was down by 13%, and the company could only muster $27 million in profit on $3.3 billion in sales (0.8% profit margin).[4] So Mr. Palmer went at it again. He abandoned the nine-unit structure of 1994 for three tighter, more centrally controlled functional organizations (sales and marketing, products, and services). The work force shrank again, to 56,000. In 1989, it had been 120,000.

It's been said that the definition of insanity is doing the same thing over and over but expecting a different result. Clearly, the organization wasn't DEC's problem, and reorganization wasn't the solution. This should have been obvious after the second reorganization. But the complexity of the system, coupled with the "Darwinian" (dynamically evolving) characteristics of the computer market, were clearly too much for traditional system analysis approaches. It's worth noting that in early 1998, Compaq Corporation bought DEC. Mr. Palmer's reorganizing days are probably over, for which the surviving 56,000 DEC employees are undoubtedly grateful.

The Need

If the NAFTAs and the Digital Equipment Corporations of the future are to be avoided, there is a pressing need for a way to engineer organizational systems that satisfies the following criteria:

- Produces positive impact on the system goal, not just component process objectives
- Models complex system functional interactions
- Reveals and contends with interrelated cause and effect among system components (specifically, separates correlation from cause and effect)
- Models solutions and verifies their effectiveness
- Identifies and overcomes implementation obstacles
- Promotes willing cooperation with change, not resistance

THE THEORY OF CONSTRAINTS

A recently developed but proven way to engineer organizational systems that satisfies all these criteria, and a few others, is the Theory of Constraints (TOC).[5] Conceived and developed over the past 15 years by E.M. Goldratt, an Israeli physicist, constraint theory provides a unique way of addressing improvement and change questions from the system level, rather than the process. TOC can be characterized as a set of concepts, principles, and measurements that focus attention on the ultimate output of the whole system, not just that of a component part of it. It includes a set of logistical tools to optimize the flow of work—whether product, service, or project—through the system, and a set of logic trees to identify core system problems (constraints), design and test solutions, and structure implementation plans. A partial bibliography of related references follows the text of this paper.

EXAMPLES OF APPLICATIONS

Constraint theory, or its tools, has been applied in a number of circumstances. Four of the most noteworthy successes have occurred at Bethlehem Steel, Ford Electronics, Harris Semiconductor, and General Motors.

Bethlehem Steel

In 1994, the staff at Bethlehem Steel-Sparrows Point reinvented the way the plant went about producing steel and satisfying its market. Before the change, Sparrows Point ran zero to minus four percent return on net assets. Quoted lead times for delivery of steel orders was 12+ weeks, and due date performance on those quotations was never any better than 70 percent, at best.[6] Customers had little faith in Bethlehem Steel. The company was slowly drowning in red ink.

By 1995, Sparrows Point had turned the situation around. Quoted lead times dropped dramatically to six weeks or less, and due date performance improved to more than 90 percent, consistently. That year, Sparrows Point actually exported 500,000 tons of steel to the international market, where American steel had not been competitive for years. Most important, Sparrows Point was the only one of Bethlehem Steel's five divisions to actually make money. Return on net assets improved to positive numbers for the first time since the 1970s.

What made the difference? The Theory of Constraints. Under the leadership of Carl Johnson, Sparrows Point's vice president for operations, the plant started producing to order, rather than to inventory, applying sound constraint management principles including an emphasis on throughput (expresses in dollars, not tons), rather than output (tons).[7] As a consequence of its commitment to constraint management, Sparrows Point has remained the one bright spot in Bethlehem Steel for the past three years.

Ford Electronics[8]

In 1989, Ford Electronics' Markham, Ontario (Canada) plant required nearly sixteen days to deliver an order of electronic components to its customers, the manufacturer's automotive assembly plants. Of that sixteen days, twelve represented the actual manufacturing cycle time. The remaining four days were used to schedule production. The Markham management applied just-in-time principles and by 1990 had reduced the manufacturing cycle time from 12 to 8 days.

In 1990, determined to drive order-to-delivery time down even further, they applied the Theory of Constraints. By 1991, manufacturing cycle time dropped another 90 percent, to less than one day (two shifts), and production scheduling dropped to one day. This improvement had two noteworthy side effects: it reduced material handling by more than 50 percent, and it liberated the equivalent of one whole plant's capacity to take on other work. It also opened 20 percent of floor space in the plant.

Harris Semiconductor[9]

In December 1988, Harris Semiconductor Corporation bought a semiconductor wafer fabrication plant in Mountaintop, Pennsylvania, from General Electric/RCA/Intersil. The plant manufactured discrete power semiconductors for the automotive industry and power control applications.

By 1991, the Mountaintop plant was losing money and facing shutdown. Over the preceding 10 years, the work force had shrunk from 3,100 to 500. However, within five years the Mountaintop plant had successfully executed a $50 million turnaround, posting a five-fold increase in net income. Nearly all of that increase accrued between 1994 and 1996.

What happened to precipitate such a dramatic turnaround? The desperate situation in 1991 certainly played a part. Among the most significant transformations was the replacement of a traditional cost accounting management approach with the Throughput-based approach developed by Goldratt. The Throughput-based approach rejects traditional fascination with gross margins, standard costs, allocation of fixed costs, and consideration of inventory as an asset. It disavows the importance of local machine and labor efficiencies, and the primacy of reducing operating costs. Instead, it emphasizes the importance of increasing system Throughput and focuses attention on the system constraint as a way of doing so. Embracing constraint management and Throughput as a primary measure of success enabled Mountaintop to concentrate on the "critical few" success elements, rather than the "trivial many".

Constraint theory proved the fallacy of the "balanced line"—the idea that equalizing the capacity of every step in a manufacturing process improves the productivity of the entire line. Most of the semiconductor industry still operates this way, however. Now all wafer fabrication facilities at Mountaintop operate on a "balanced flow" concept, rather than striving for high labor and machine efficiencies at every step of the process. William Levinson, staff engineer and industrial statistician at Mountaintop, credits the Theory of Constraints for the huge increases in overall plant productivity.

General Motors[10]

General Motors competes with Ford, Chrysler, and the Japanese for a share of the US market in automobile sales. Like other industries in highly competitive markets, the auto industry finds itself less able than ever before to compete on the basis of price alone. By the early 1990s, after billions of dollars of investment in quality improvements, the fortunes of the "big three" US auto makers began to level out the competitive advantages of the Japanese—quality and price. The differences in quality between American and Japanese cars became less pronounced, and, owing to a favorable dollar-yen exchange rate, American auto manufacturers enjoyed a slight price advantage.

General Motors (GM) began to search for a decisive advantage over the rest of the field. Using the Theory of Constraints logic trees, GM identified a way to provide a quantum increase in customer satisfaction and service while actually reducing the cost of providing cars to the buying public.[11]

Almost all automobile dealers in the US make most of their money selling cars directly off their lots—on-hand stocks, which they buy from the manufacturers in a limited assortment of styles, colors, and optional equipment, but not all possible combinations. As a result, the odds are fairly high that most customers won't get exactly what they want in a car. They may get their preferred style and color, but not some desired optional equipment. Or, more likely, they may end up with equipment they don't really want. All automobile dealers face this problem, including those selling Japanese cars.

American manufacturers accept custom orders from dealers, but most are incapable of delivering these "made to order" cars back to the dealers in less than 60 to 85 days. Most customers aren't willing to wait that long for a new car, so they often settle for something other than what they actually want. Dealers, too, prefer to sell off the lot, because they already have money tied up in the on-site inventory— money they need to recover quickly— and a custom order doesn't help them do that. Special orders aren't even an option with Japanese cars, which are usually offered in a few standard packages. The odds of a customer getting, and paying for, unwanted options are even higher than for American cars.

GM executives applied the logic trees developed by Goldratt to solving this problem. By building current reality trees to define the cause-effect relationship in the existing situation, they were able to identify several root causes constraining their ability to deliver custom orders quickly. Using future reality trees, they developed and verified several creative solutions. They identified and "trimmed" negative branches and constructed prerequisite trees and transition trees to implement the solution.

GM found they could eliminate weeks of unnecessary delay in delivering a custom order. Theoretically, they thought, delivery time for about 15 percent of custom-ordered cars could be reduced to a maximum of 19 days.[12] By establishing regional distribution centers, they could deliver the remaining 85 percent in about two days! They set about testing the new process with Cadillac in the state of Florida. After an initial test period of several months, GM found that all but a very few vehicles had been delivered within the expected time—and those few were each only a day late. GM subsequently expanded the test to all Cadillac dealerships in the southwestern United States, with similar results.

By 1999, GM expects to roll out this concept to its other divisions as well.[13] The expectation is that most, if not all, cars eventually will be built to order, rather than to a sales forecast. In other words, big year-end unsold inventories would become a thing of the past, and dealers wouldn't have to maintain large on-site inventories. The final result could be a complete conversion of automobile production from a "push" to a "pull" system, which could yield savings of up to 20 percent in the cost of providing GM cars to the market.[14] Making the change happen now depends on their discipline and commitment.

THE TOC LOGICAL THINKING PROCESS

As indicated earlier, the Theory of Constraints is comprised of a set of concepts and principles, production and project management tools, and a series of logic trees. The balance of this paper will focus on the logic trees as a means of system modeling and optimization.

The logical thinking process developed by Goldratt is composed of five distinct trees: current reality tree, "evaporating cloud", future reality tree, prerequisite tree, and transition tree.[15] These trees were originally designed to be applied in sequence to accomplish a complete analysis of any complex system. Subsequent to their development, however, Goldratt realized that each tree might also be productively applied in isolation from the rest. For instance, it is not necessary to construct a current reality tree, future reality tree, prerequisite tree, or transition tree if all one needs to do is resolve a conflict. However, to the extent that a conflict stagnates overall system performance, construction of one or more of the other logic trees might be required.

Managers at any level can use this thinking process to provide answers to the three questions that determine their ultimate success in optimizing the whole system:

- *What* to change
- What to change *to*
- *How* to effect the change

Current Reality Tree (CRT)[16]

The current reality tree is designed to trace an unbroken chain of cause and effect from the clearly visible indications that the system isn't performing as it should—the undesirable effects— backward to the (usually) hidden root causes. Typically, CRTs reveal that several seemingly unrelated undesirable effects originate from the same root cause. Recognizing this phenomenon can be very important to system improvers, because it facilitates economy of force: applying minimum effort to a few critical points, yet effecting the maximum system improvement from those efforts. Much like a pinch point in an hourglass, those few root causes usually turn out to be the constraints that prevent the system from achieving higher levels of performance. And invariably those constraints turn out to be some kind of policy.

The current reality, as a system analysis tool, provides the answer to the question *what to change.* It clearly depicts the causal relationships between seemingly disparate parts of the system. An example of a typical current reality tree is included in Figure 1. This analysis explains why America's highways are generally in such deplorable condition.[17] The undesirable effects experienced by the driving public (road closures, traffic congestion caused by road maintenance, potholes, and accidents) are directly attributable, by unbroken chain of cause and effect back to the constraint— a bad law (policy) passed by the U.S. congress.

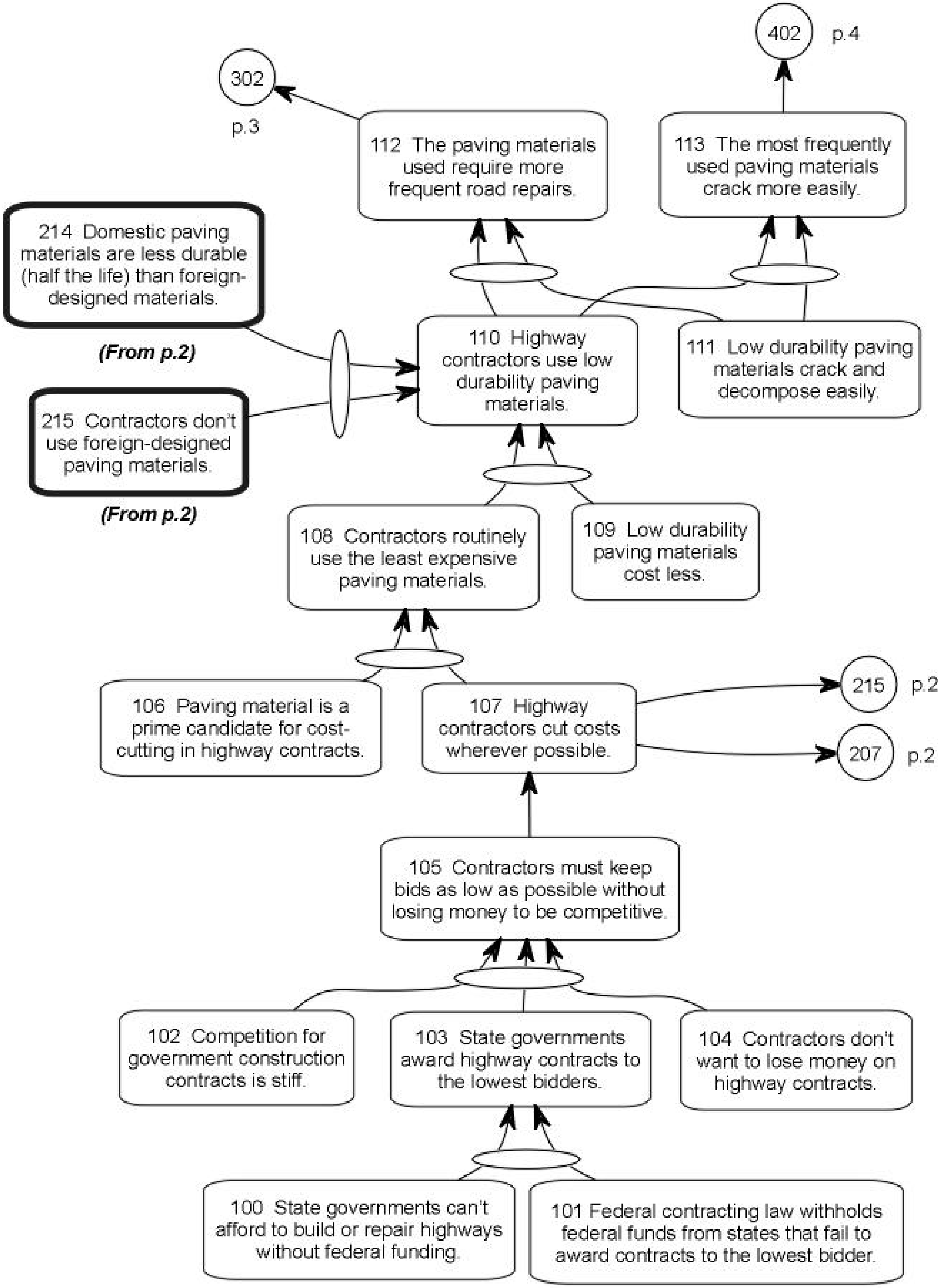
> NOTE: When reading the current reality tree, future reality tree, and transition tree, verbalize the statement in the block at the tail of each arrow, preceding the statement with the word "If...". Precede the statement at the head of the arrow with the word "...then...". EXAMPLE: "***If*** state governments can't afford to build or repair highways without federal funding, ***and*** federal contracting law withholds federal funds from states that fail to award contracts to the lowest bidder, ***then*** state governments award highway contracts to the lowest bidder."

"Evaporating Cloud" (Conflict Resolution Diagram)[18]

It's one thing to identify a root cause. It's another to do something about it. Root causes often exist because powerful motivations or forces keep them in place. Changing a policy that is the root cause of some high level undesirable effects might not be easy. Often such policies are in place because they currently serve—or at one time did—some constructive purpose. A proposal to change an existing way of doing things is likely to pose a conflict: keep the status quo versus institute something new. Goldratt conceived the "evaporating cloud," a kind of conflict resolution diagram, to address underlying policy conflict.

The evaporating cloud (EC) is a five-element tree that expresses both sides of a bipolar conflict. The two sides are joined at a common objective, usually a system level purpose of some kind. The objective can only be achieved by satisfying some intermediate conditions or requirements, which, because they are necessary conditions for the objective, are by definition not in conflict themselves. But these requirements are satisfied by taking some kind of action—the policies that are actually in conflict.

Figure 2 shows a continuation of the topic analyzed in the current reality tree (Figure 1). In the EC, the existing policy, "Award contracts to the lowest bidder," comes from the root cause (block 103) in the CRT. Eliminating the undesirable effects in the CRT requires that we do something to change that root cause, thus destroying the causality that leads to those undesirable effects. Consequently, we're motivated to do the opposite: *don't* award contracts to the lowest bidder. This action, or policy change, is a prerequisite to satisfying the condition "highest quality (long lasting) highways." But it's also in direct conflict with the other prerequisite, our existing policy, and it's this conflict that stagnates any possible progress toward resolving the root cause.



This current reality tree constructed from information provided in the article
"Why Our Roads Go to Pot," by Betsy Dance (*The Washington Monthly*, November 1991).

Figure 1a. CURRENT REALITY TREE: "Why Our Roads Go to Pot"

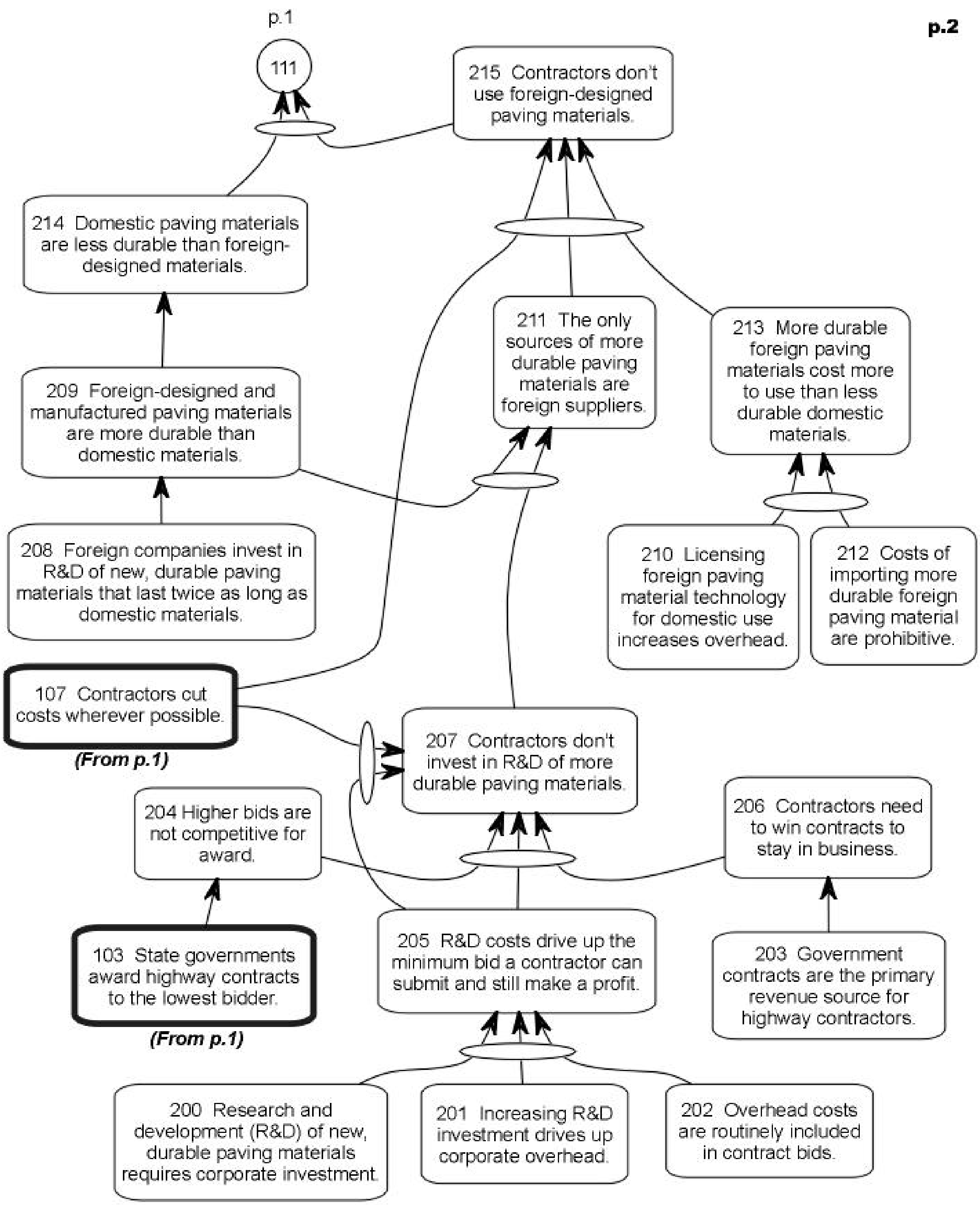


Figure 1b. CURRENT REALITY TREE: "Why Our Roads Go to Pot"

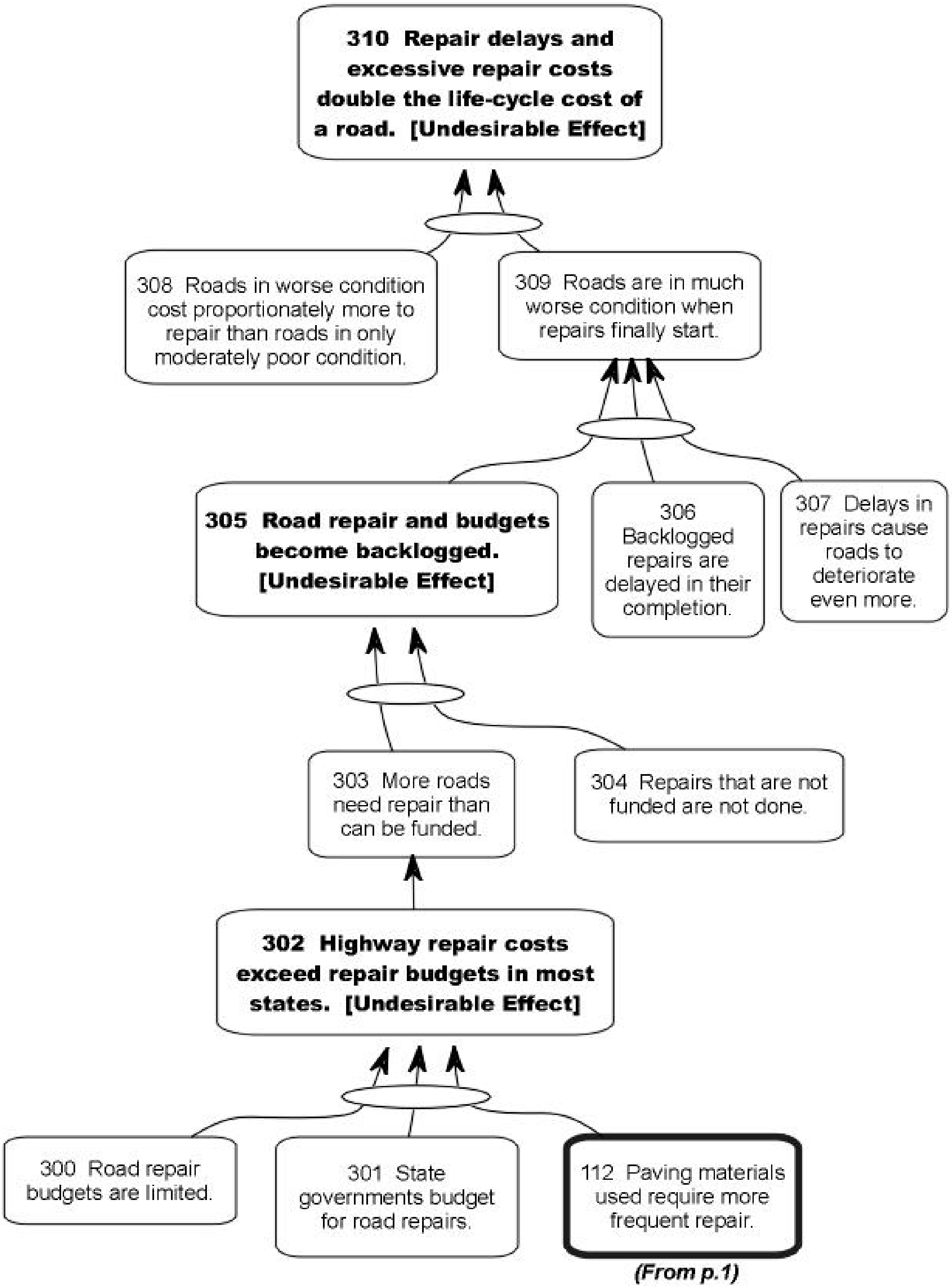


Figure 1c. CURRENT REALITY TREE: "Why Our Roads Go to Pot"

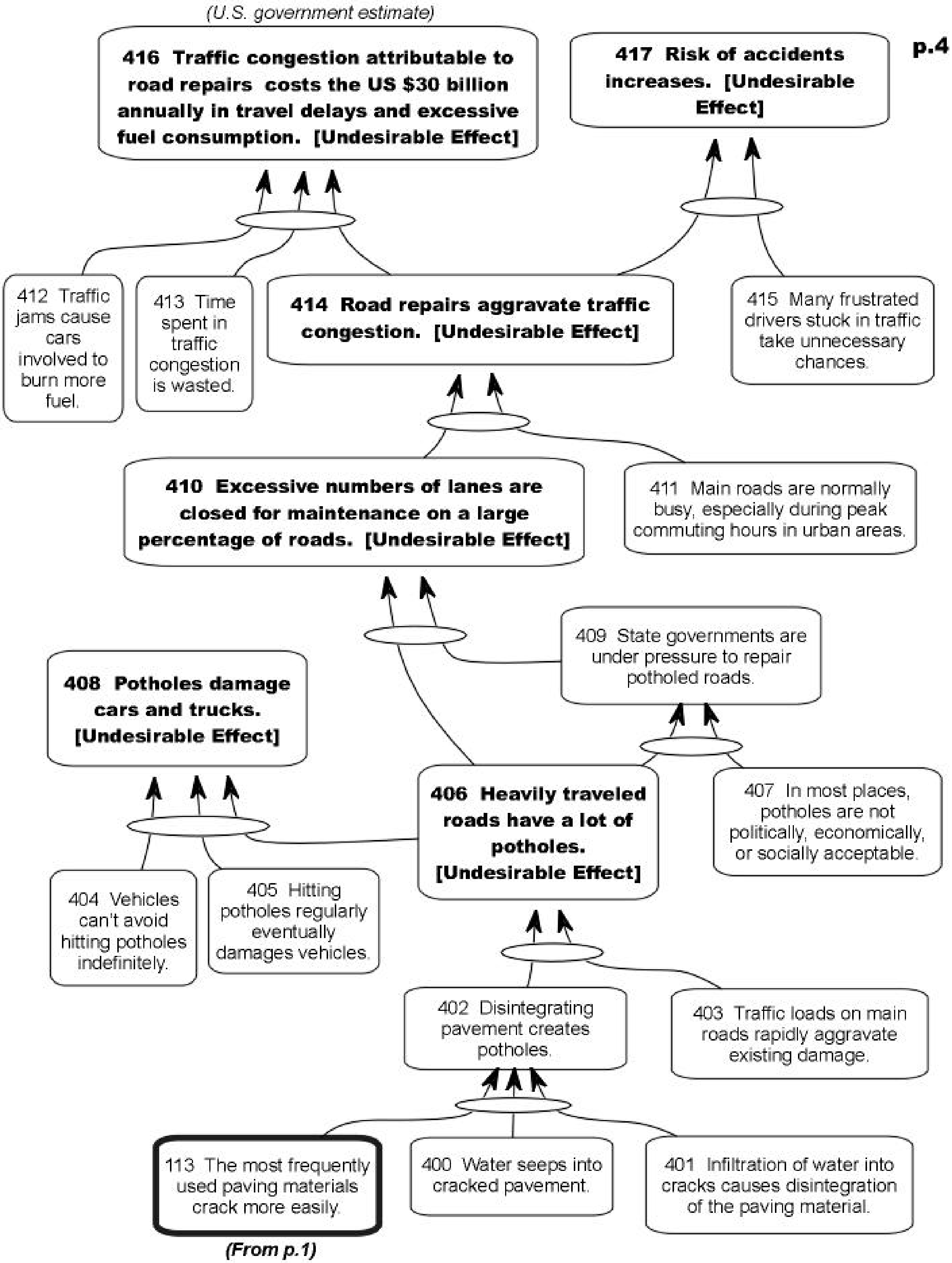
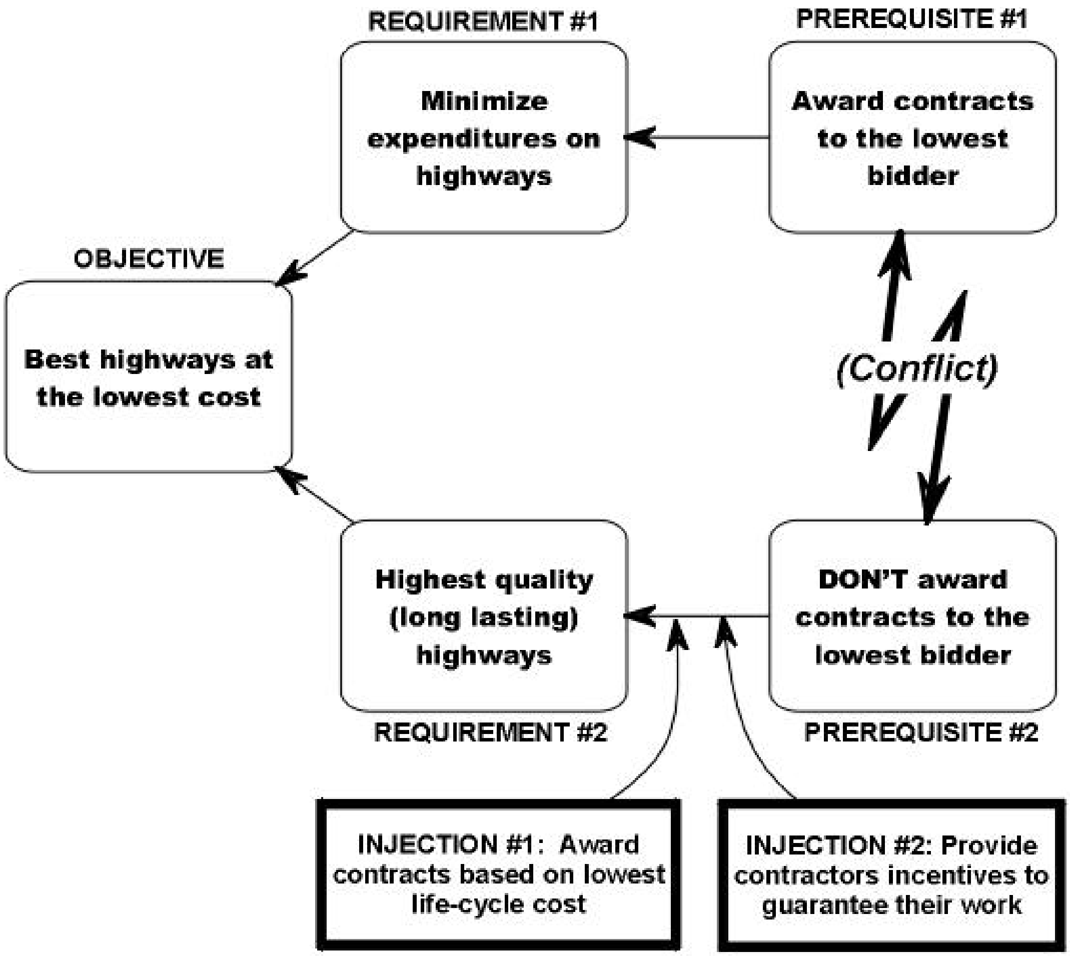


Figure 1d. CURRENT REALITY TREE: "Why Our Roads Go to Pot"



INVALID ASSUMPTIONS UNDERLYING THE CONFLICT

1. Initial acquisition cost is an accurate representation of total life-cycle costs.
2. Subsequent highway repair never competes with initial acquisition (new highways) for the same funding in later years.
3. Lowest bidders are motivated to make highways last as long as possible.
4. It is never less expensive in the long run to spend a little more money during initial acquisition
5. The lowest bidder always provides the highest quality, longest lasting product

Figure 2. Evaporating Cloud: "Why Our Roads Don't Improve"

Ultimately, an EC is broken (and, by extension, the conflict itself) by "injecting" some new action or policy into the situation that will still satisfy both the requirements but allow us to eliminate one—or possibly both—prerequisites. In other words, the requirements are satisfied without having to endure one or more of the conflicting policies. In Figure 2, we'd like to be able to retain the lowest bidder prerequisite, because it's demanded by law. But we'd also like to realize high quality road work. There are two injections that will allow us to keep costs down and still have high quality roads. One is to interpret *lowest cost* to mean minimum financial expenditures over the lifetime of the road. The second is to motivate contractors to guarantee their work.

Future Reality Tree (FRT)[19]

When the CRD is complete, the constraint-breaking process has gone as far as most problem-solving methodologies ever take anyone: idea generation. At this point, most analysts must figure out how to implement the new idea themselves. The TOC thinking process, however, continues into implementation. But before doing so, the thinking process offers a capability that no other integrated problem-solving process does: it *verifies the effectiveness of the ideas* (injections) generated in the EC.

The means for accomplishing test and verification is the future reality tree. It's similar to the CRT, except that instead of displaying existing reality, it shows the cause and effect that will occur if the injections are executed. Through an unbroken chain of causality, it shows how the future will unfold to produce *desired*, rather than undesirable effects. If the ideas produced by the CRD are not really viable, it will be impossible to build a FRT leading to desired effects that will withstand challenge by the rules of logic.

However, as Eric Sevareid once observed, "the chief cause of problems is solutions." Even if it *is* possible to prove that the injections will achieve the desired effects, it's also possible that these new actions (policies) will produce new effects that are undesirable—maybe even devastating. But the FRT can identify these hidden pitfalls, too. One of the attributes of the FRT is the *negative branch*, which indicates causality paths that lead from the injection to new undesirable effects that did not previously exist.

Figures 3 and 4 shows a typical FRT with a negative branch. These were prepared to show how *America Online®*, the largest provider of Internet services in the U.S., could have anticipated the devastating effects that resulted from policy changes they made with the best of intentions. Note that in this FRT, the logic of cause and effect definitely leads to some desirable outcomes. But before it gets to those outcomes, it also produces some major negative impacts on the company. *America Online®* now enjoys even more success than it did before its policy change, so the validity of the FRT is confirmed. But had the company's management known how to construct a FRT, they might have avoided the pain (not to mention the unnecessary financial cost) they incurred in reaching those desired effects.

In revealing the negative branch, it becomes possible to create an *additional injection*, or idea, to "trim" the negative branch from the FRT—really, to keep it from ever growing in the first place. In the case of *America Online®*, two branch-trimming injections would have been required. The first would have been to accurately assess the new demand to be placed on its hardware and communication lines. The second would have been to delay implementing its new rates structure until the increased system capacity could be added to handle the anticipated jump in load.

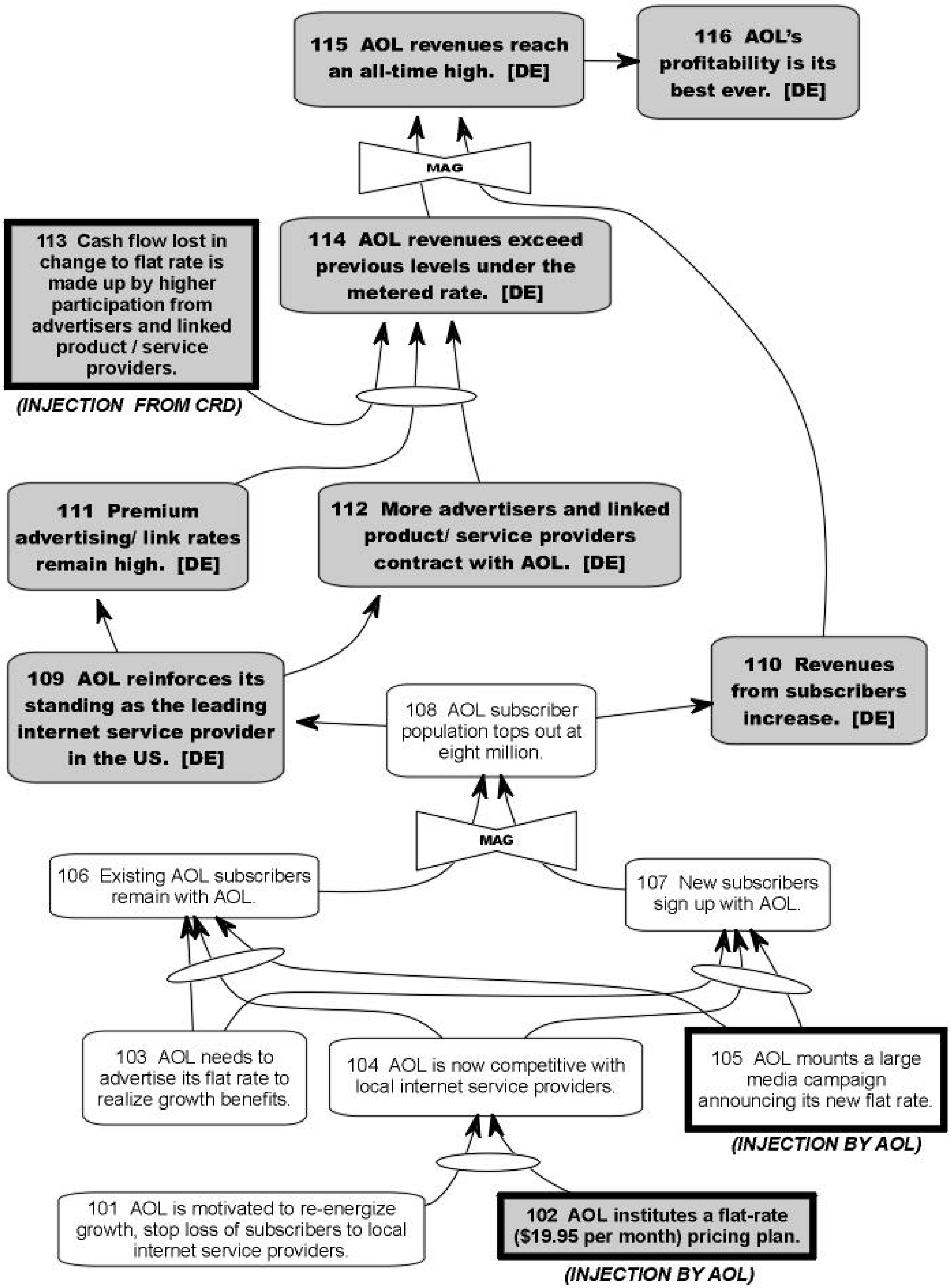


Figure 3. FUTURE REALITY TREE: "All Circuits Are Busy..."

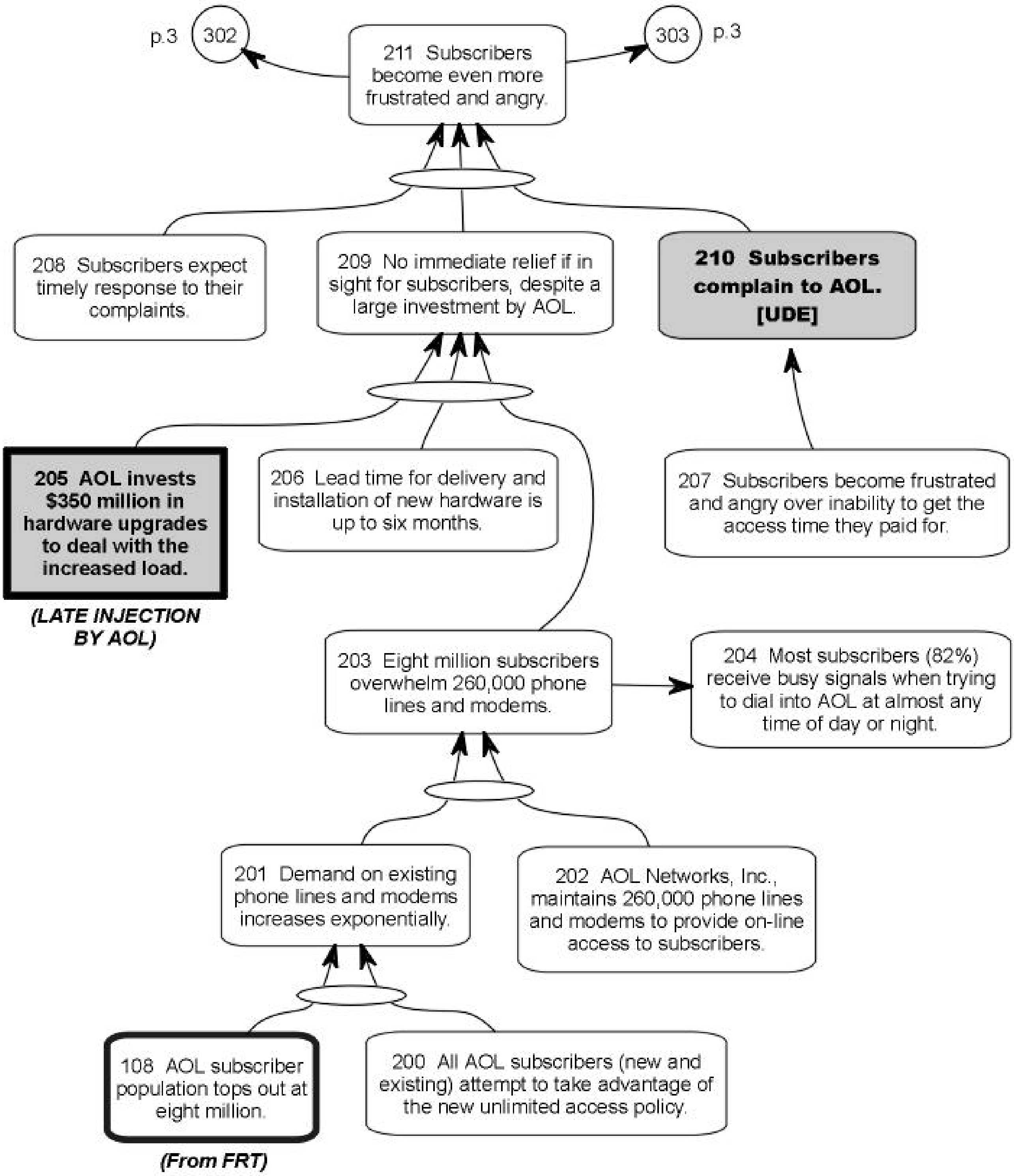


Figure 4a. NEGATIVE BRANCH: "All Circuits Are Busy"

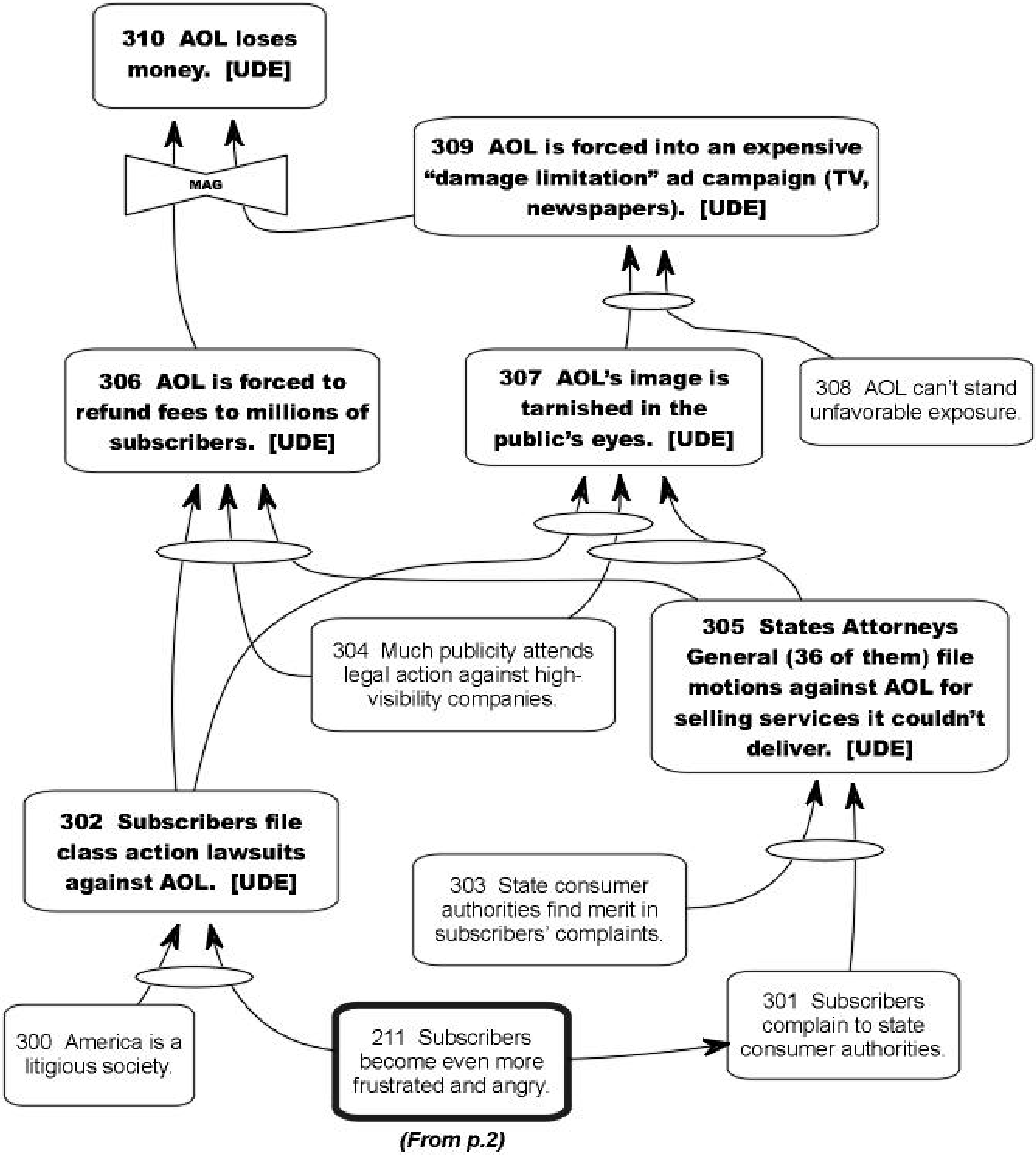


Figure 4b. NEGATIVE BRANCH: "All Circuits Are Busy"

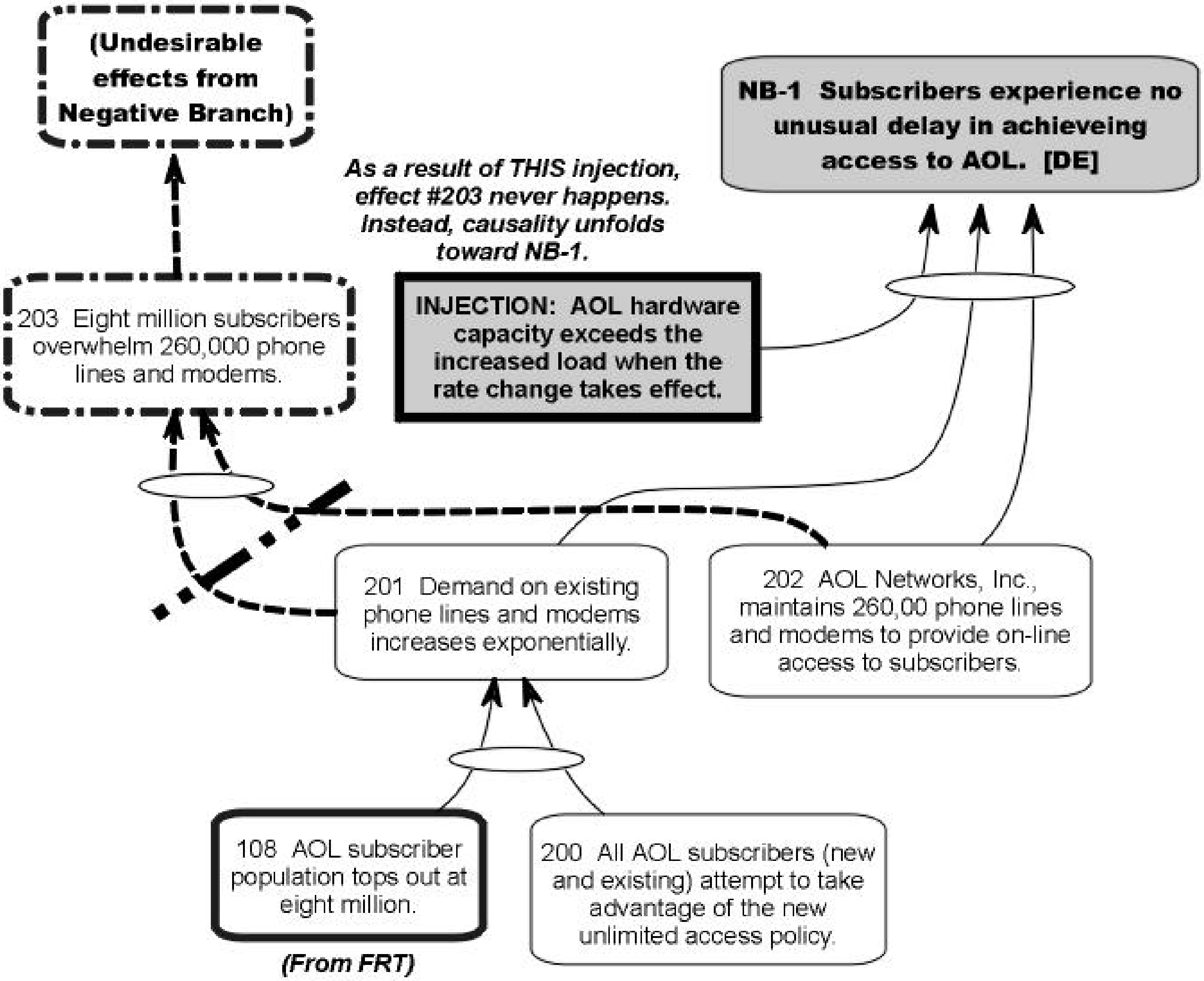


Figure 4c. NEGATIVE BRANCH (Trimmed)
"All Circuits are NO LONGER busy"

Prerequisite Tree (PRT) and Transition Tree (TT)[20]

Once the proposed injections are verified with a FRT, the toughest challenge begins: *execution*. The logical thinking process is unique among problem-solving methodologies in that it includes trees specifically designed to facilitate execution of change.

The prerequisite tree serves several important purposes. First, it helps identify the obstacles to implementation—those conditions that could prevent successful execution. Second, it determines the sequence in which these obstacles must be overcome. Some actions clearly must precede others; the PRT can show us the dependencies. Third, it helps determine what specific intermediate objectives must be achieved to overcome each obstacle. Finally, the whole prerequisite tree constitutes a framework of milestones that can serve as the basis for a detailed implementation plan.

The transition tree converts intermediate objectives, or milestones, into detailed, step-by-step actions, with accountability for accomplishment for each one built in. The TT can reduce implementation to a series of checklist steps that can be delegated to people charged with their completion. Accomplishment of the steps in each transition tree will naturally lead to achievement of the intermediate objectives and the accomplishment of the organizational change.

Because prerequisite and transition trees often can become fairly complex, only partial examples of each are provided in Figures 5 and 6[21] to illustrate the nature of these trees. These two figures are continuations of the *America Online®* situation introduced in Figures 3 and 4. Note that in Figure 5, the prerequisite doesn't show everything needed to complete the change, only the obstacles—those things or conditions not already available—that must be provided for. Figure 6 shows how the transition tree adds the detailed actions needed to make the plan truly executable.

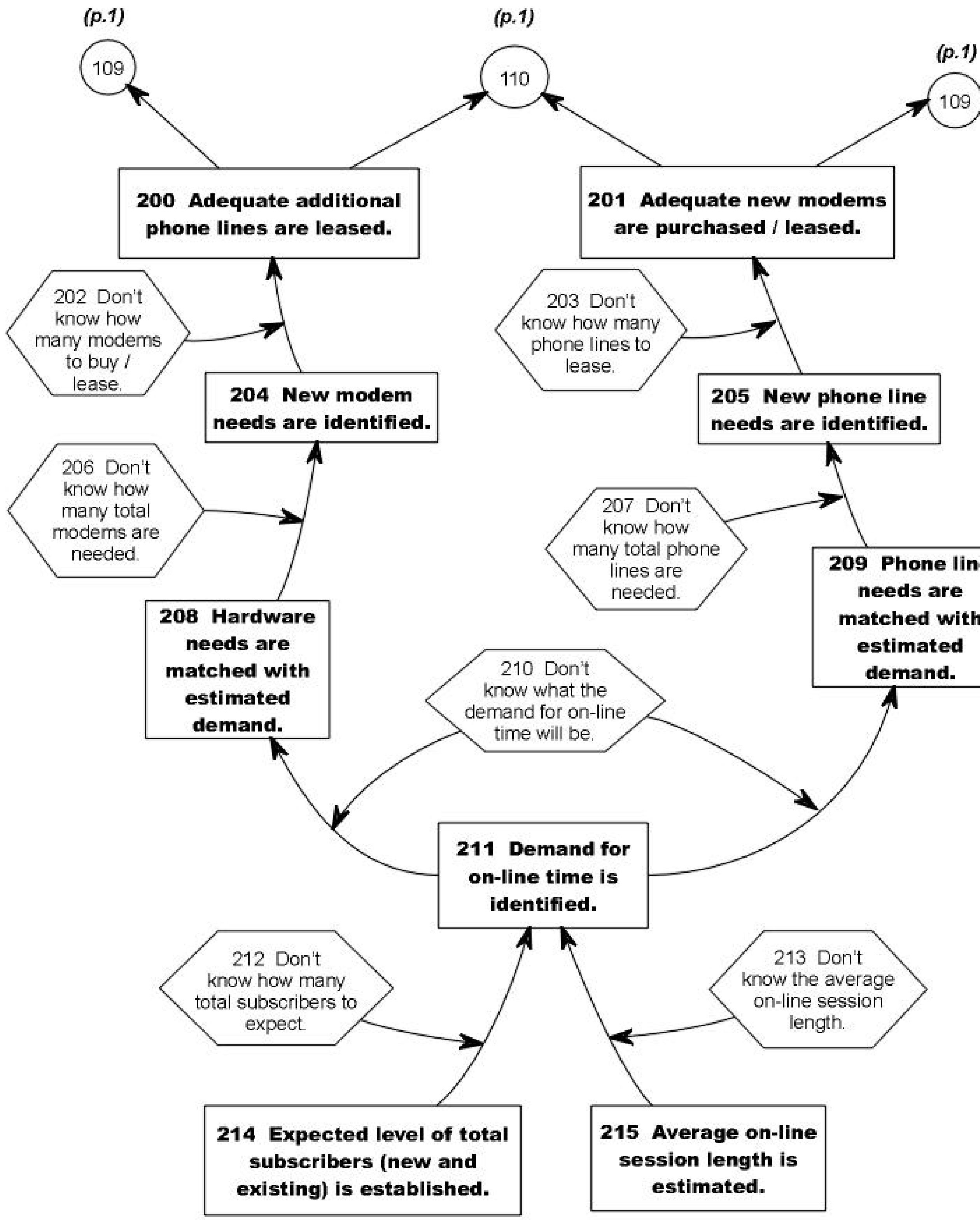


Figure 5b. PREREQUISITE TREE: AOL Avoids Disaster

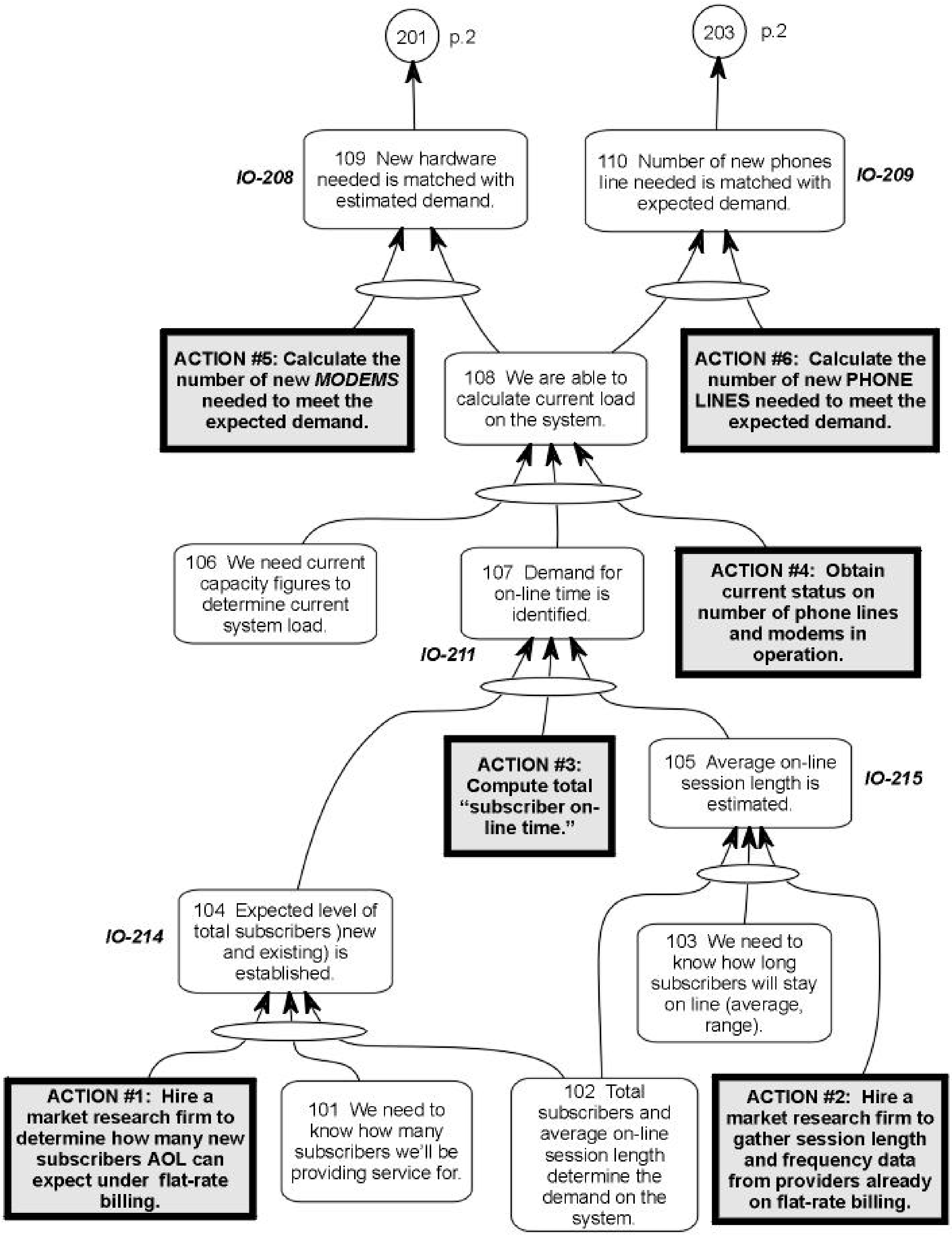


Figure 6a. TRANSITION TREE: AOL Avoids Disaster

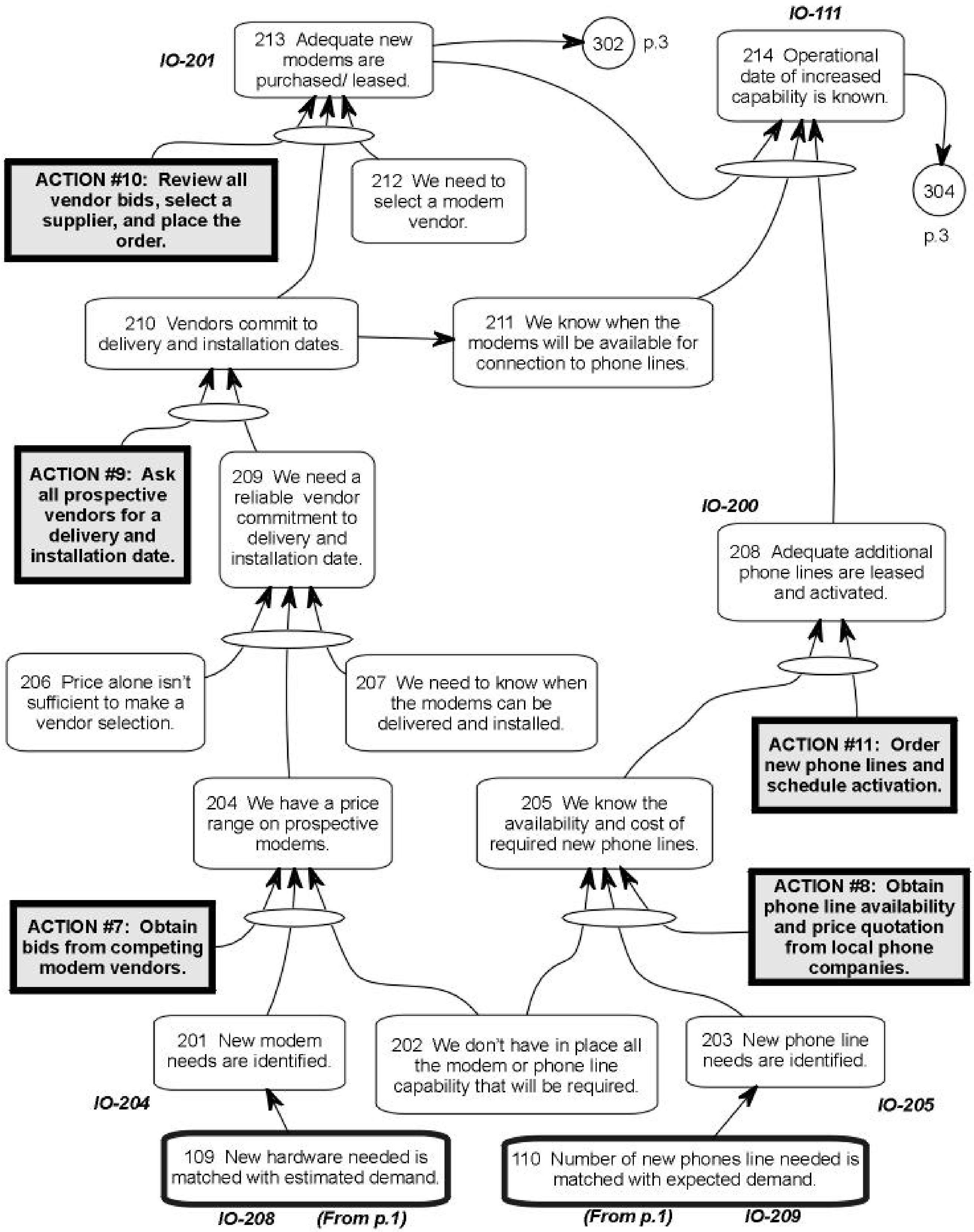


Figure 6b. TRANSITION TREE: AOL Avoids Disaster

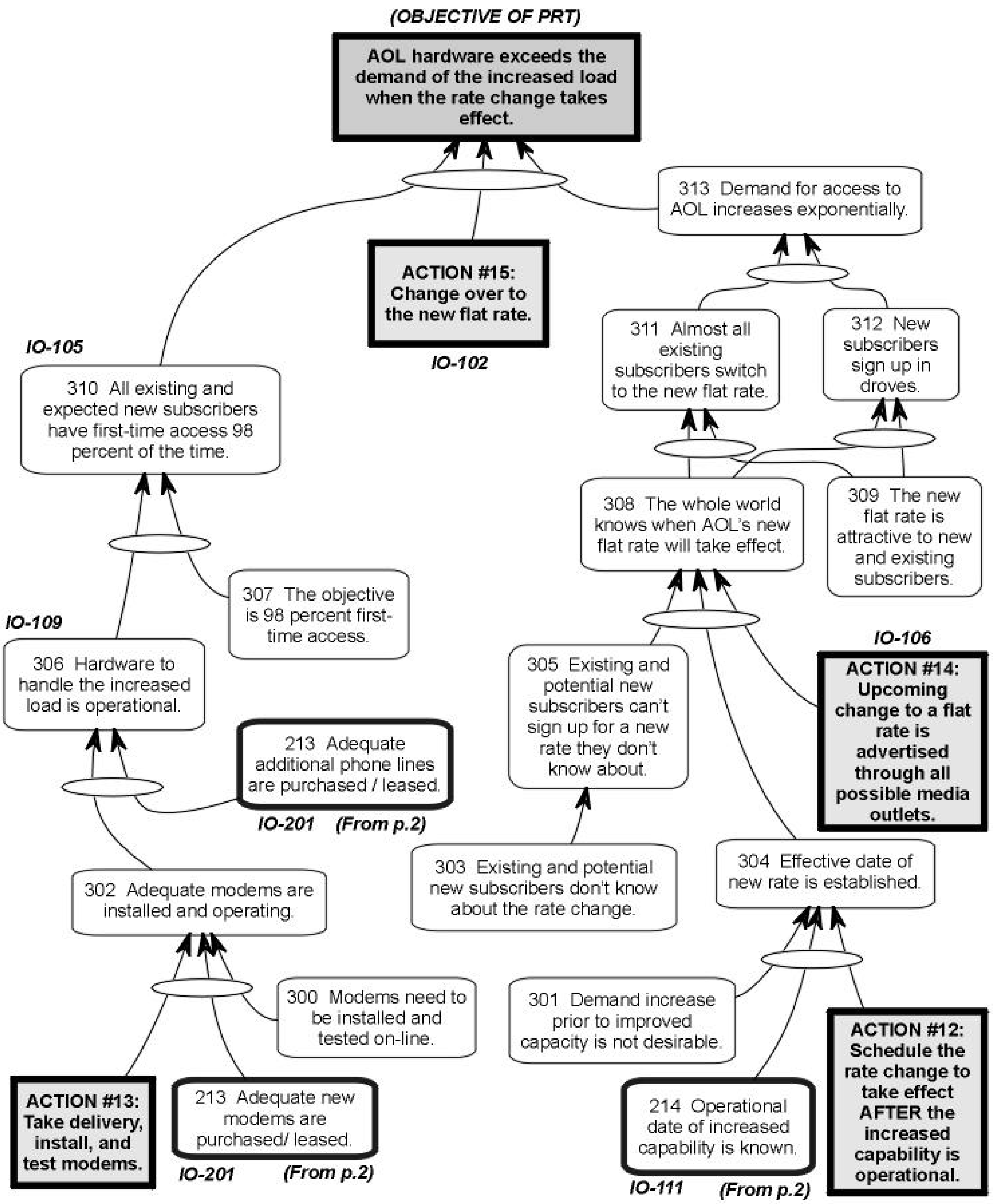


Figure 6c. TRANSITION TREE: AOL Avoids Disaster

CONCLUSION

The Theory of Constraints and the logical thinking process are not a panacea for all system ills. They don't replace a thorough understanding of the system (the profound knowledge referred to by W. Edwards Deming[22]), the motivation to improve a system, or the willingness to accept accountability for action. What they *do* provide for the first time is a structured framework and a logical methodology for coordinating and optimizing whole systems, not merely aggregating the piecemeal improvements of components.

ENDNOTES

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6. Video tape of Dennis Keifer, vice-president for sales and marketing, Bethlehem Steel-Sparrows Point, September, 1995.

7. Video tape of Carl Johnson, vice-president for operations, Bethlehem Steel-Sparrows Point, September, 1995.

8. Video tape, "One-Day Manufacturing Cycle Time," produced by Ford Electronics Markham, Ontario (Canada) plant, 1992.

9. William A. Levinson (ed.). *Leading the Way to Competitive Excellence: The Harris Mountaintop Case Study*. Milwaukee, WI: ASQ Quality Press, 1998.

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13. Ibid., p. A3.

14. Gabriella Stern. "GM Expands Its Experiment to Improve Cadillac's Distribution, Cut Inefficiency". *The Wall Street Journal*, Wednesday, February 8, 1995.

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16. Ibid., ch. 3.

17. Betsy Dance, "Why America's Roads Go to Pot," *The Atlantic Monthly*, November 1991. Reprinted in *Readers Digest*, April 1992, pp. 121-124.

18. Dettmer, *Goldratt's Theory of Constraints*, ch. 4.

19. Ibid., ch. 5.

20. Ibid., ch. 6, 7.

21. Dettmer, *Breaking the Constraints to World-Class Performance*, ch. 9, 10.

22. W. Edward Deming, *The New Economics for Industry Government,, and Education.* Cambridge, MA: MIT Center for Advanced Engineering Study, 1993, ch. 4.