队列长度 G_{Qw} 和拥塞服务节点数量 $N_{congest}$ 这两个指标进行评估.全局负载排队队列长度用于评估任务等待队列中制造任务的数量,该值越小,表示任务全局等待的时间较小,任务执行的效率较高,t 时刻的负载队列排队长度按公式(7)进行计算(其中,num 表示制造服务总数,Q_w 表示任务等待队列长度):

$$G_{Q_w}(t)=\sum_{i=1}^{num}Q_w(i,t) \tag{7}$$

拥塞服务节点数量用于评估制造服务网络中处于满载状态的节点个数.当服务节点处于满载状态时,其不再接受任何任务请求.因此,满载节点越多,网络的可用节点数量就越少,可用性越差.具体按公式(8)进行计算:

$$N_{congest}(t)=\sum_{i=1}^{num}a(i,t),\ \text{where } a(i,t)=\begin{cases}1, & \text{if } L(i)=l_{\max}\\ 0, & \text{if } L(i)<l_{\max}\end{cases} \tag{8}$$

图 10 为不同时刻(取 m=20,n=50;λ=30,60,90req/s)下的全局负载排队队列长度和拥塞服务节点数目.

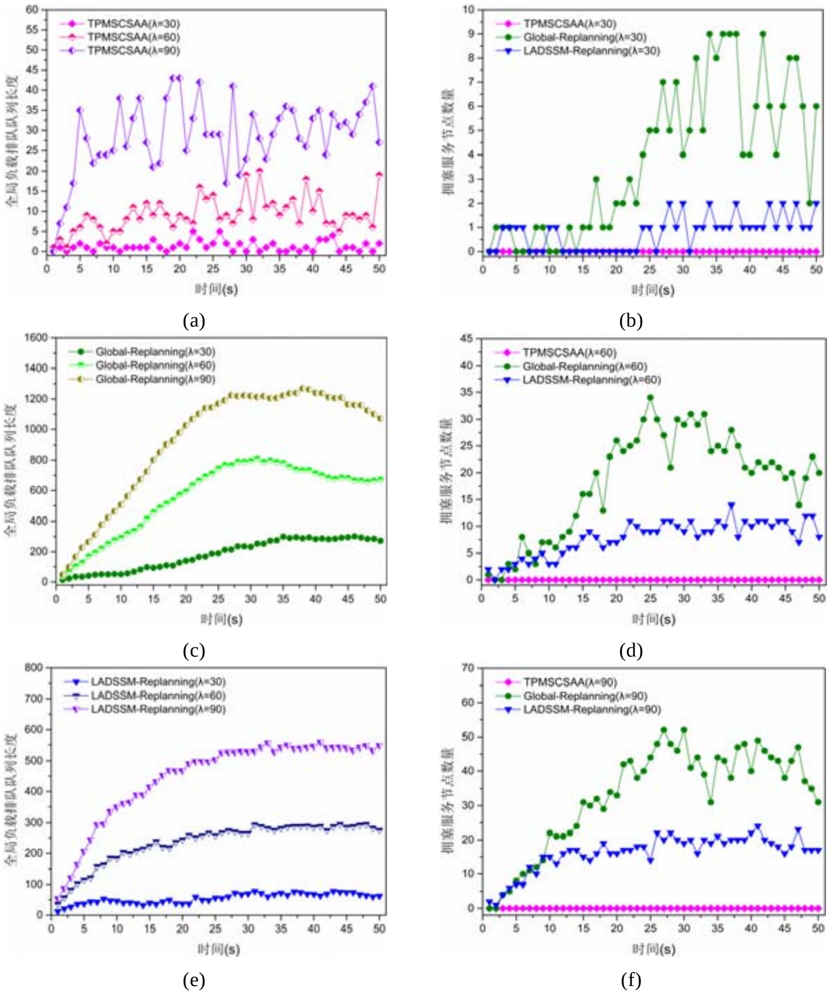

Fig.10 Global optimization capability of load queue at different task arrival rate

图 10 不同任务到达速率下全局负载队列优化能力

由图 10(a)、图 10(c)、图 10(e)可知,TPMSCSAA 算法对全局排队队列的优化能力远远高于其余两种算法,在较短的时间内就能使负载排队队列保持稳定的状态,即使在制造任务量较大(λ=90)的情况下,TPMSCSAA 算法还能使负载排队队列长度稳态值保持在 35 上下,而 Global-Replanning 算法和 LADSSM-Replanning 的稳态值

分别为 1150 和 550 左右.可见:本文算法能使服务网络的总体任务等待数量较小,从而降低了负载对 QoS(响应时间)的影响,提高了服务网络的执行效率和制造任务的执行成功率.同时,由图 10(b)、图 10(d)、图 10(f)可知,TPMSCSAA 算法能够有效避免服务节点的拥塞,通过对负载队列的优化,减少对优质 QoS 服务的过度调用,在服务网络负载容量一定的情况下,使资源的可用性大幅度提高.

(4) 制造服务组合平均 QoS 效用(AU_{QoS})

平均 QoS 效用是指对于所有执行成功的制造任务所对应的制造服务组合的 QoS 效用的平均值,按公式(9)进行计算:

$$AU_{QoS}=\frac{\sum_{i=1}^{N_s}U(SC)_i}{N_s} \tag{9}$$

其中,N_s 表示满足端到端 QoS 约束的制造任务数量;$U(i)$代表制造服务组合的 QoS 效用,其值按公式(10)计算:

$$U(SC)=\sum_{k=1}^{r}\frac{q_k(SC)-QSC_k^{\min}}{QSC_k^{\max}-QSC_k^{\min}}\cdot w_k \tag{10}$$

其中,$q_k(SC)$表示服务组合中第 k 维属性值,$QSC_k^{\max}$ 表示所有执行成功的制造服务组合中 QoS 第 k 维属性最大值,$QSC_k^{\min}$ 表示所有执行成功的制造服务组合中 QoS 第 k 维属性的最小值.由于本文选取的是消极指标,按公式(10)计算得到的服务组合 QoS 值越小,代表 QoS 优化效果越好.因此,AU_{QoS} 的值越小越好.该指标体现了制造服务组合算法对 QoS 的优化能力.图 11 为 3 种算法在不同制造任务到达速率下的平均 QoS 效用值.

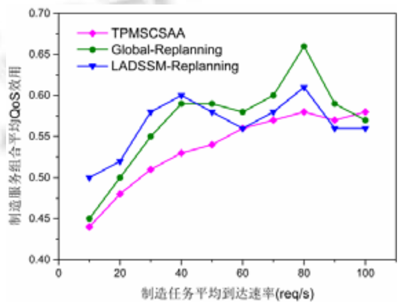

Fig.11 Average QoS utility of manufacturing service composition

图 11 制造服务组合平均 QoS 效用

由图 11 可知,随着制造任务平均到达速率的增加,Global-Replaning 算法和 LADSSM-Replanning 算法上升速度较快,在λ>40 之后,表现出相同的变化趋势,制造服务组合的平均 QoS 产生大幅度的波动;而 TPMSCSAA 算法由于对负载进行了优化,制造服务组合的平均 QoS 上升缓慢,随后(λ>70)逐渐趋于平稳.在负载较高(λ>90)时,TPMSCSAA 算法会略高于其余两种算法.原因在于在满足端到端 QoS 约束,保证全局制造任务的执行成功率的前提下,TPMSCSAA 算法选择了较次优的制造服务.

6 结论及未来的工作

本文以复杂网络的视角,研究了云制造系统中制造任务与制造服务的动态管理,构建了动态匹配网络理论模型,基于此,提出了一种三阶段的制造服务组合自适应方法(TPMSCSAA).该方法能够通过负载队列模型对 QoS 进行动态评估,以负载和动态 QoS 为优化目标,将最优制造服务组合问题转化为制造服务网络中最短路径的搜索,实现制造服务的动态调度.同时,根据实时获取的制造任务变更和制造服务变更动态更新制造任务网络和制造服务网络,然后基于动态调度算法实现制造服务组合的自动调整.通过对电梯设计服务组合的验证,从制造任务执行成功率、制造服务社团负载均衡度、全局负载队列优化能力和制造服务组合平均 QoS 效用证明了 TPMSCSAA 对动态环境具有很好的自适应能力.值得一提的是,TPMSCSAA 不仅可以运用于像电梯设计服务之类的软制造资源,也可以运用于机床加工等具有独占性的硬制造资源,只需将服务执行队列的容量设置为 1 即

可.此外,对于服务时间较长(几天乃至数月)的制造业务流程,制造资源的变动更加频繁,TPMSCSAA 可以根据动态环境在线分步组合,更具灵活性.

未来的工作将对以下几方面作深入研究:(1) 由于本文动态 QoS 模型只考虑响应时间和成本,下一步将研究其他 QoS 指标,如可靠性、可信度与负载之间的关系,提升动态 QoS 模型的通用性;(2) 进一步研究服务网络中统计特性(如节点的度、介数等)对服务组合的影响,对自适应方法进行优化.

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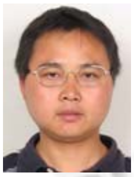

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